FORM PTO-1390 (Modified) (REV 11-2000) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**	ATTORNEY'S DOCKET NUMBER **DN1999118USA**
	U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR **10/018208**

INTERNATIONAL APPLICATION NO. **PCT/US99/29827**	INTERNATIONAL FILING DATE **December 15, 1999**	PRIORITY DATE CLAIMED **May 17, 1999**

TITLE OF INVENTION
PROGRAMMABLE MODULATION INDEX FOR TRANSPONDER

APPLICANT(S) FOR DO/EO/US
YONES, Dale Lee

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.

2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.

3. ☐ This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include itens (5), (6), (9) and (24) indicated below.

4. ☐ The US has been elected by the expiration of 19 months from the priority date (Article 31).

5. ☒ A copy of the International Application as filed (35 U.S.C. 371 (c) (2))

     a. ☐ is attached hereto (required only if not communicated by the International Bureau).

     b. ☒ has been communicated by the International Bureau.

     c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).

6. ☐ An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).

     a. ☐ is attached hereto.

     b. ☐ has been previously submitted under 35 U.S.C. 154(d)(4).

7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3))

     a. ☐ are attached hereto (required only if not communicated by the International Bureau).

     b. ☒ have been communicated by the International Bureau.

     c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.

     d. ☐ have not been made and will not be made.

8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).

9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).

10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).

11. ☒ A copy of the International Preliminary Examination Report (PCT/IPEA/409).

12. ☒ A copy of the International Search Report (PCT/ISA/210).

Items 13 to 20 below concern document(s) or information included:

13. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.

14. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.

15. ☒ A **FIRST** preliminary amendment.

16. ☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.

17. ☐ A substitute specification.

18. ☐ A change of power of attorney and/or address letter.

19. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.

20. ☐ A second copy of the published international application under 35 U.S.C. 154(d)(4).

21. ☐ A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).

22. ☒ Certificate of Mailing by Express Mail

23. ☐ Other items or information:

U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR) **10/018208**	INTERNATIONAL APPLICATION NO. **PCT/US99/29827**	ATTORNEY'S DOCKET NUMBER **DN1999118USA**

24. The following fees are submitted:.	CALCULATIONS PTO USE ONLY

BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :

☐ Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1040.00**

☒ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$890.00**

☐ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$740.00**

☐ International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$710.00**

☐ International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**

ENTER APPROPRIATE BASIC FEE AMOUNT =	**$890.00**	

Surcharge of **$130.00** for furnishing the oath or declaration later than ☒ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).	**$130.00**	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	25 - 20 =	5	x $18.00	**$90.00**	
Independent claims	4 - 3 =	1	x $84.00	**$84.00**	
Multiple Dependent Claims **(check if applicable).**			☐	**$0.00**	

TOTAL OF ABOVE CALCULATIONS =	**$1,194.00**	

Applicant claims small entity status. See 37 CFR 1.27). The fees indicated above are reduced by 1/2.	**$0.00**	

SUBTOTAL =	**$1,194.00**	

Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (f)). +	**$0.00**	

TOTAL NATIONAL FEE =	**$1,194.00**	

Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) **(check if applicable).** ☐	**$0.00**	

TOTAL FEES ENCLOSED =	**$1,194.00**	

	Amount to be: refunded	$
	charged	$

a. ☐ A check in the amount of _____ to cover the above fees is enclosed.

b. ☒ Please charge my Deposit Account No. **07-1725** in the amount of **$1,194.00** to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. **07-1725** A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING: Information on this form may become public. Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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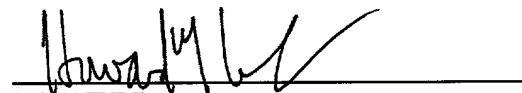
SIGNATURE

Howard M. Cohn

NAME

25,808

REGISTRATION NUMBER

November 9, 2001

DATE

CERTIFICATE OF MAILING BY "EXPRESS MAIL" (37 CFR 1.10)	Docket No.
Applicant(s): Yones	DN1999118USA

Serial No.	Filing Date **concurrently herewith**	Examiner	Group Art Unit

Invention: **PROGRAMMABLE MODULATION INDEX FOR TRANSPONDER**

I hereby certify that the following correspondence:

TRANSMITTAL LETTER

(Identify type of correspondence)

is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under

37 CFR 1.10 in an envelope addressed to: The Assistant Commissioner for Patents, Washington, D.C. 20231 on

Novmber 9, 2001
(Date)

Catherine Senkfor
(Typed or Printed Name of Person Mailing Correspondence)

(Signature of Person Mailing Correspondence)

ET709527782US
("Express Mail" Mailing Label Number)

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P06A/REV02

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re : Application of Yones
For : **PROGRAMMABLE MODULATION INDEX FOR TRANSPONDER**
Serial No. :
Filed : Concurrently herewith
Group Art Unit :
Examiner :
Our Docket No. : DN1999118USA

November 9, 2001

ASSISTANT COMMISSIONER OF PATENTS
Washington, D.C. 20231

PRELIMINARY AMENDMENT

Sir:

This is a preliminary amendment filed with a 35 U.S.C. 365 filing of a PCT International

Application designating the United States.

Please amend the referenced application as follows:

IN THE CLAIMS

Please cancel claims 1-21 and replace with claims 22-42 as follows:

22.   An RF transponder comprising an antenna system characterized by:

a programmable load connected to the antenna system for transmission modulation.

23.   An RF transponder, according to claim 22, characterized in that the programmable

load comprises:

a plurality of first output stage transistors connected to a first terminal of the antenna

system;

a corresponding plurality of second output stage transistors connected to a second

terminal of the antenna system; and

control logic for determining which ones of the first output stage transistors and

which ones of the second output stage transistors are used to modulate the antenna system.

24.   An RF transponder, according to claim 23, characterized by:

an EEPROM storing programmed settings for driving the control logic.

25.   An RF transponder, according to claim 22, characterized by:

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a power supply and level shifters connected to the programmable load, wherein voltage changes in the power supply dynamically vary a magnitude of the programmable load according to power available in the transponder.

26. An RF transponder, according to claim 22, characterized by:

a gate for disconnecting modulation of the antenna system in response to a reset signal.

27. An RF transponder comprising:

an antenna system characterized by:

a dynamically variable load, comprising:

a load connected to the antenna system for transmission modulation; and

a power supply and level shifters connected to the load, wherein voltage changes of the power supply dynamically vary the magnitude of the load according to power available in the transponder.

28. An RF transponder, according to claim 27, characterized in that:

the dynamically variable load further comprises elements for programmable variation of the magnitude of the load on the antenna system, the elements comprising:

a plurality of first output stage transistors connected to a first terminal of the antenna system;

a corresponding plurality of second output stage transistors connected to a second terminal of the antenna system; and

control logic for determining which ones of the first output stage transistors and which ones of the second output stage transistors are used to modulate the antenna system.

29. An RF transponder, according to claim 28, characterized by:

an EEPROM storing programmed settings for driving the control logic.

30. An RF transponder, according to claim 27, characterized by:

control logic connected for modulating the dynamically variable load, wherein the control logic has a control signal input formed in a gate by logically combining a system clock signal and a data stream.

31. An RF transponder, according to claim 30, characterized by:

a sync delay circuit for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

32. An RF transponder, according to claim 27, characterized by:

a gate for interrupting modulation of the antenna system in response to a reset signal.

33. An RF transponder comprising:

an antenna system; and

circuitry for applying modulation to an RF signal received by the antenna system, characterized by:

a modulation load connected to the antenna system;

control logic for controlling the modulation load;

a first gate providing a control signal to the control logic, wherein the first gate logically combines a system clock signal and a data stream; and

a sync delay circuit for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

34. An RF transponder, according to claim 33, characterized by:

a second gate interposed between the first gate and the control logic for disconnecting modulation of the antenna system in response to a reset signal.

35. Method for controlling RF signal modulation in a passive transponder which comprises an antenna system, circuitry for applying modulation to an RF signal received by the antenna system, and circuitry for deriving transponder power from the received RF signal, characterized by:

providing a modulation load connected to the antenna system and modulated under the control of a control signal formed by logically combining a system clock signal and a data stream; and

delaying the system clock signal in order to synchronize the system clock signal with the data stream.

36. Method, according to claim 35, characterized by:

forming a phase-shift keyed type of control signal, for producing phase-shift keyed modulation of the RF signal received by the antenna system.

37. Method, according to claim 36, characterized in that:

the phase-shift keyed control signal uses a system clock signal having half the frequency of the RF signal received by the antenna system; and

the data stream is a signal clocked at a fraction of the frequency of the RF signal

received by the antenna system.

38.   Method, according to claim 37, characterized in that:

the fraction is one-thirty-second (1/32)

39.   Method, according to claim 35, characterized by:

optimizing RF signal modulation performance by utilizing a modulation index having a magnitude which is adjusted according to programmed trim settings stored in the transponder.

40.   Method, according to claim 39, characterized by:

binary adjustment of the modulation index as determined by bits of the programmed trim settings.

41.   Method, according to claim 35, characterized by:

a modulation index having a magnitude which is adjusted dynamically in proportion to a power of the RF signal received by the antenna system.

42.   Method, according to claim 35, characterized by:

preventing RF signal modulation if the power derived from the RF signal received by the antenna system is too low to provide transponder power adequate for stable transponder operation including RF signal modulation.

REMARKS

The claims have been amended to delete the numbers identifying elements, which were originally incorporated to comply with PCT practice. A separate copy of the claims as amended is included for the Examiner's convenience.

Favorable examination and consideration are respectfully requested.

Respectfully submitted,
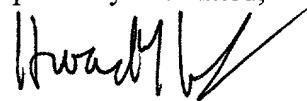
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CLAIMS:

22.   An RF transponder comprising an antenna system characterized by:

a programmable load connected to the antenna system for transmission modulation.

23.   An RF transponder, according to claim 22, characterized in that the programmable load comprises:

a plurality of first output stage transistors connected to a first terminal of the antenna system;

a corresponding plurality of second output stage transistors connected to a second terminal of the antenna system; and

control logic for determining which ones of the first output stage transistors and which ones of the second output stage transistors are used to modulate the antenna system.

24.   An RF transponder, according to claim 23, characterized by:

an EEPROM storing programmed settings for driving the control logic.

25.   An RF transponder, according to claim 22, characterized by:

a power supply and level shifters connected to the programmable load, wherein voltage changes in the power supply dynamically vary a magnitude of the programmable load according to power available in the transponder.

26.   An RF transponder, according to claim 22, characterized by:

a gate for disconnecting modulation of the antenna system in response to a reset signal.

27.   An RF transponder comprising:

an antenna system characterized by:

a dynamically variable load, comprising:

a load connected to the antenna system for transmission modulation; and

a power supply and level shifters connected to the load, wherein voltage changes of the power supply dynamically vary the magnitude of the load according to power available in the transponder.

28.   An RF transponder, according to claim 27, characterized in that:

the dynamically variable load further comprises elements for programmable variation of the magnitude of the load on the antenna system, the elements comprising:

a plurality of first output stage transistors connected to a first terminal of the

antenna system;

a corresponding plurality of second output stage transistors connected to a second terminal of the antenna system; and

control logic for determining which ones of the first output stage transistors and which ones of the second output stage transistors are used to modulate the antenna system.

29. An RF transponder, according to claim 28, characterized by:

an EEPROM storing programmed settings for driving the control logic.

30. An RF transponder, according to claim 27, characterized by:

control logic connected for modulating the dynamically variable load, wherein the control logic has a control signal input formed in a gate by logically combining a system clock signal and a data stream.

31. An RF transponder, according to claim 30, characterized by:

a sync delay circuit for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

32. An RF transponder, according to claim 27, characterized by:

a gate for interrupting modulation of the antenna system in response to a reset signal.

33. An RF transponder comprising:

an antenna system; and

circuitry for applying modulation to an RF signal received by the antenna system, characterized by:

a modulation load connected to the antenna system;

control logic for controlling the modulation load;

a first gate providing a control signal to the control logic, wherein the first gate logically combines a system clock signal and a data stream; and

a sync delay circuit for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

34. An RF transponder, according to claim 33, characterized by:

a second gate interposed between the first gate and the control logic for disconnecting modulation of the antenna system in response to a reset signal.

35. Method for controlling RF signal modulation in a passive transponder which comprises an antenna system, circuitry for applying modulation to an RF signal received by

the antenna system, and circuitry for deriving transponder power from the received RF signal, characterized by:

provideing a modulation load connected to the antenna system and modulated under the control of a control signal formed by logically combining a system clock signal and a data stream; and

delaying the system clock signal in order to synchronize the system clock signal with the data stream.

36.   Method, according to claim 35, characterized by:

forming a phase-shift keyed type of control signal, for producing phase-shift keyed modulation of the RF signal received by the antenna system.

37.   Method, according to claim 36, characterized in that:

the phase-shift keyed control signal uses a system clock signal having half the frequency of the RF signal received by the antenna system; and

the data stream is a signal clocked at a fraction of the frequency of the RF signal received by the antenna system.

38.   Method, according to claim 37, characterized in that:

the fraction is one-thirty-second (1/32)

39.   Method, according to claim 35, characterized by:

optimizing RF signal modulation performance by utilizing a modulation index having a magnitude which is adjusted according to programmed trim settings stored in the transponder.

40.   Method, according to claim 39, characterized by:

binary adjustment of the modulation index as determined by bits of the programmed trim settings.

41.   Method, according to claim 35, characterized by:

a modulation index having a magnitude which is adjusted dynamically in proportion to a power of the RF signal received by the antenna system.

42.   Method, according to claim 35, characterized by:

preventing RF signal modulation if the power derived from the RF signal received by the antenna system is too low to provide transponder power adequate for stable transponder operation including RF signal modulation.

DN1999118PCT

PROGRAMMABLE MODULATION INDEX FOR TRANSPONDER

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application relates to PCT applications Serial No. PCT/US99/29890 entitled RELAXATION OSCILLATOR FOR TRANSPONDER, Publication No. WO00/69663 entitled POWER ON RESET FOR TRANSPONDER and Serial No. PCT/US99/29840

10   entitled PROGRAMMABLE TRIMMER FOR TRANSPONDER, each having a filing date concurrent with that of the present application

This application is a continuation-in-part of commonly-owned, copending PCT applications Serial Nos. PCT/U99/29668 and PCT/US99/29606 both filed on 14 December 1999, which in turn are continuation-in-part of commonly-owned, copending PCT Publication

15   Nos.WO99/52723, WO99/52724 and WO/53279 all filed on 14 April 1998.

This application claims the benefit of U.S. Provisional Patent Application No. 60/134,460, filed May 17, 1999 by Yones.

TECHNICAL FIELD OF THE INVENTION

The present invention relates to monitoring pressure and temperature and, more

20   particularly in conjunction with transponders associated with the tires for transmitting pressure and temperature measurements to an external (e.g., on-board) receiver (reader, or reader/interrogator).

BACKGROUND OF THE INVENTION

Safe, efficient and economical operation of a motor vehicle depends, to a significant

25   degree, on maintaining correct air pressure in all (each) of the tires of the motor vehicle. Operating the vehicle with low tire pressure may result in excessive tire wear, steering difficulties, poor road-handling, and poor gasoline mileage, all of which are exacerbated when the tire pressure goes to zero in the case of a "flat" tire.

The need to monitor tire pressure when the tire is in use is highlighted in the context

30   of "run-flat" (driven deflated) tires, tires which are capable of being used in a completely deflated condition. Such run-flat tires, as disclosed for example in commonly-owned USP 5,368,082, incorporated in its entirety by reference herein, may incorporate reinforced sidewalls, mechanisms for securing the tire bead to the rim, and a non-pneumatic tire (donut) within the pneumatic tire to enable a driver to maintain control over the vehicle after a

AMENDED SHEET

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catastrophic pressure loss, and are evolving to the point where it is becoming less and less noticeable to the driver that the tire has become deflated. The broad purpose behind using run-flat tires is to enable a driver of a vehicle to continue driving on a deflated pneumatic tire for a limited distance (e.g., 50 miles, or 80 kilometers) prior to getting the tire repaired,

rather than stopping on the side of the road to repair the deflated tire. Hence, it is generally desirable to provide a low tire pressure warning system within in the vehicle to alert (e.g., via a light or a buzzer) the driver to the loss of air pressure in a pneumatic tire.

To this end, a number of electronic devices and systems are known for monitoring the pressure of pneumatic tires, and providing the operator of the vehicle with either an indication of the current tire pressure or alerting the operator when the pressure has dropped below a predetermined threshold level.

For example, USP 4,578,992 (Galasko, et al; 04/86), incorporated in its entirety herein, discloses a tire pressure indicating device including a coil and a pressure-sensitive capacitor forming a passive oscillatory circuit having a natural resonant frequency which varies with tire pressure due to changes caused to the capacitance value of the capacitor. The circuit is energized by pulses supplied by a coil positioned outside the tire and secured to the vehicle, and the natural frequency of the passive oscillatory circuit is detected. The natural frequency of the coil/capacitor circuit is indicative of the pressure on the pressure-sensitive capacitor.

It is also known to monitor tire pressure with an electronic device which is not merely a passive resonant circuit, but rather is capable of transmitting a radio frequency (RF) signal indicative of the tire pressure to a remotely-located receiver. Such a "transmitting device" may have its own power supply and may be activated only when the pressure drops below a predetermined threshold. Alternatively, the transmitting device may be activated ("turned ON") by an RF signal from the remotely-located receiver, in which case the receiver is considered to be an "interrogator". Additionally, the transmitting device may be powered by an RF signal from the interrogator. Additionally, the electronic device which monitors the tire pressure may have the capability of receiving information from the interrogator, in which case the electronic device is referred to as a "transponder".

As used herein, a "transponder" is an electronic device capable of receiving and transmitting radio frequency signals, and impressing variable information (data) in a suitable format upon the transmitted signal indicative of a measured condition (e.g., tire pressure) or conditions (e.g., tire pressure, temperature, revolutions), as well as optionally impressing fixed information (e.g., tire ID) on the transmitted signal, as well as optionally responding to information which may be present on the received signal. The typical condition of

paramount interest for pneumatic tires is tire pressure. "Passive" transponders are
transponders powered by the energy of a signal received from the interrogator. "Active"
transponders are transponders having their own power supply (e.g., a battery), and include
active transponders which remain in a "sleep" mode, using minimal power, until "woken
5   up" by a signal from an interrogator, or by an internal periodic timer, or by an attached
device. As used herein, the term "tag" refers either to a transponder having transmitting
and receiving capability, or to a device that has only transmitting capability. Generally, tags
which are transponders are preferred in the system of the present invention. As used herein,
the term "tire-pressure monitoring system" (TPMS) indicates an overall system comprising
10   tags within the tires and a receiver which may be an interrogator disposed within the
vehicle.

It is known to mount a tag, and associated condition sensor (e.g., pressure sensor)
within each tire of a vehicle, and to collect information from each of these transponders with
a common single interrogator (or receiver), and to alert a driver of the vehicle to a low tire
15   pressure condition requiring correction (e.g., replacing the tire). For example, USP
5,540,092 (Handfield, et al.; 1996), incorporated in its entirety by reference herein,
discloses a system and method for monitoring a pneumatic tire. Figure 1 therein illustrates a
pneumatic tire monitoring system (20) comprising a transponder (22) and a receiving unit
(24).

20   Examples of RF transponders suitable for installation in a pneumatic tire are
disclosed in U.S. Patent No. 5,451,959 (Schuermann; 09/95), U.S. Patent No. 5,661,651
(Geschke, et al.; 08/97), and U.S. Patent No. 5,581,023 (Handfield, et al.; 12/96), all
incorporated in their entirety by reference herein. The described transponder systems
include interrogation units, pressure sensors and/or temperature sensors associated with the
25   transponder, and various techniques for establishing the identity of the tire/transponder in
multiple transponder systems. In most cases, such transponders require battery power.

In some instances, a transponder may be implemented as an integrated circuit (IC)
chip. Typically, the IC chip and other components are mounted and/or connected to a
substrate such as a printed circuit board (PCB).

30   Some proposed systems have relatively complex transponder-sensor capabilities,
including measurement and reporting of tire rotations and speed, along with tire ID,

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temperature, and pressure. For example: USP 5,562,787 (Koch, et al.; 1996), and USP

5,731,754 (Lee, Jr., et al.; 1998), incorporated in their entirety by reference herein.

TRANSPONDER ENVIRONMENTAL CONSIDERATIONS

The environment within which a tire-mounted transponder must reliably operate,

5   including during manufacture and in use, presents numerous challenges to the successful

operation of the transducer. For example, the sensors (e.g., pressure, temperature) used

with the transponder preferably will have an operating temperature range of up to 125°C,

and should be able to withstand a manufacturing temperature of approximately 177°C. For

truck tire applications, the pressure sensor must have an operating pressure range of from

10   about 50 psi to about 120 psi (from about 345 kPa to about 827 kPa), and should be able to

withstand pressure during manufacture of the tire of up to about 400 psi (about 2759 kPa).

The accuracy, including the sum of all contributors to its inaccuracy, should be on the order

of plus or minus 3% of full scale. Repeatability and stability of the pressure signal should

fall within a specified accuracy range.

15   However it is implemented, a tire transponder (tag) must therefore be able to operate

reliably despite a wide range of pressures and temperatures. Additionally, a tire transponder

must be able to withstand significant mechanical shocks such as may be encountered when a

vehicle drives over a speed bump or a pothole.

A device which can be used to indicate if a transponder or the tire has been exposed

20   to excessive, potentially damaging temperatures is the "MTMS" device or Maximum

Temperature Memory Switch developed by. Prof. Mehran Mehregany of Case Western

Reserve University. It is a micro-machined silicon device that switches to a closed state at a

certain high-temperature point. The sensor switches from an "open" high resistance state

of, for example, over 1 mega-ohm to a "closed" low resistance state of, for example, less

25   than 100 ohm.

Although it is generally well known to use pressure transducers in pneumatic tires,

in association with electronic circuitry for transmitting pressure data, these pressure-data

systems for tires have been plagued by difficulties inherent in the tire environment. Such

difficulties include effectively and reliably coupling RF signals into and out of the tire, the

30   rugged use the tire and electronic components are subjected to, as well as the possibility of

deleterious effects on the tire from incorporation of the pressure transducer and electronics

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in a tire/wheel system. In the context of "passive" RF transponders which are powered by an external reader/interrogator, another problem is generating predictable and stable voltage levels within the transponder so that the circuitry within the transponder can perform to its design specification.

5   Suitable pressure transducers for use with a tire-mounted transponder include:

(a) piezoelectric transducers;

(b) piezoresistive devices, such as are disclosed in USP 3,893,228 (George, et al.; 1975) and in USP 4,317,216 (Gragg, Jr.; 1982);

(c) silicon capacitive pressure transducers, such as are disclosed in USP 4,701,826
10   (Mikkor; 1987), USP 5,528,452 (Ko; 1996), USP 5,706,565 (Sparks, et al.; 1998), and WO00/02028 (Ko, et al.; filed July 7, 1999);

(d) devices formed of a variable-conductive laminate of conductance ink; and

(e) devices formed of a variable-conductance elastomeric composition.

THE EFFECT OF TEMPERATURE ON GAS PRESSURE

15   In a broad sense, for a mass of any gas in a state of thermal equilibrium, pressure P, temperature T, and volume V can readily be measured. For low enough values of the density, experiment shows that (1) for a given mass of gas held at a constant temperature, the pressure is inversely proportional to the volume (Boyle's law), and (2) for a given mass of gas held at a constant pressure, the volume is directly proportional to the temperature
20   (law of Charles and Gay-Lussac). This leads to the "equation of state" of an ideal gas, or the "ideal gas law":

$PV = \mu RT$

where:

μ is the mass of the gas in moles; and

25   R is a constant associated with the gas.

Thus, for a contained (fixed) volume of gas, such as air contained within a pneumatic tire, an increase in temperature (T) will manifest itself as an increase in pressure (P).

Because of the ideal gas law relationship, it is recognized that in the context of
30   pneumatic tires, one problem that arises during operation of tire pressure sensors of any kind is that tires heat up as they are run for longer periods of time. When a tire heats up, air

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which is confined within the essentially constant and closed volume of the tire expands, thus causing increased pressure within the tire, though the overall amount of air within the tire remains the same. Since the pressure nominally is different, a tire pressure sensor can provide different pressure readings when a tire is hot than would be the case if the tire were cold. This is why tire and vehicle manufacturers recommend that owners check their tire pressure when the tire is cold. Of course, with a remote tire pressure sensor, an operator may receive a continuous indication of tire pressure within the vehicle, but the indication may be inaccurate because of the temperature change. Thus, it is necessary to compensate for changes in temperature of the inflating medium ("gas" or air) within the pneumatic tire.

Patents dealing in one way or another with gas law effects in pneumatic tires include:

USP 3,596,509 (Raffelli; 1971), USP 4,335,283 (Migrin; 1982), USP 4,126,772 (Pappas, et al.; 1978), USP 4,909,074 (Gerresheim, et al.; 1990), USP 5,050,110 (Rott; 1991), USP 5,230,243 (Reinecke; 1993), USP 4,966,034 (Bock, et al.; 1990), USP 5,140,851 (Hettrich, et al.; 1992), USP 4,567,459 (Folger, et al.; 1986), all of which are incorporated in their entirety by reference herein.

USP 4,893,110 (Hebert; 1990), incorporated in its entirety by reference herein, discloses a tire monitoring device using pressure and temperature measurements to detect anomalies. As mentioned therein, a ratio of temperature and pressure provides a first approximation of a number of moles of gas in the tire, which should remain constant barring a leak of inflation fluid from the tire. (column 1, lines 18-26). More particularly, on each wheel are installed sensors (4) for pressure and sensors (6) for temperature of the tire, as well as elements (8 and 10) for transmitting the measured values as coded signals to a computer (12) on board the vehicle, such as disclosed in the aforementioned USP 4,703,650. The computer processes the measured values for pressure and temperature for each tire, and estimates for the pressure/temperature ratio (P/T estimate) are calculated for each wheel. Generally, the ratio for one of the tires is compared with the ratio for at least another one of the tires, and an alarm is output when a result (N) of the comparison deviates from a predetermined range of values.

TECHNIQUES FOR TRANSMITTING PRESSURE AND TEMPERATURE READINGS FROM A TIRE

Given that pressure and temperature conditions within a pneumatic tire can both be

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measured, various techniques have been proposed to transmit signals indicative of the

measured pressure and temperature conditions to an external interrogator/receiver. For

example, the following patents are incorporated in their entirety by reference herein:

        - transmit the signals individually, distinguished by phase displacements: USP

5   4,174,515 (Marzolf; 1979);

        - multiplex the signals: USP 5,285,189 (Nowicki, et al.; 1994), USP 5,297,424

(Sackett; 1994);

        - encoding the signals as separate segments of a data word: USP 5,231,872 (Bowler,

et al.; 1993), and USP 4,695,823 (Vernon; 1987) which also incorporates both the telemetry

10   and the pressure and/or temperature sensors on the same integrated circuit chip;

        - transmission between coils mounted on the wheel and on the vehicle: USP

4,567,459 (Folger, et al.; 1986);

        - use a frequency-shift key (FSK) signal: USP 5,228,337 (Sharpe, et al.; 1993);

        - backscatter-modulate the RF signal from the interrogator with the tire condition

15   parameter data from the sensors, then return the backscatter modulated signal to the

interrogator: USP 5,731,754 (Lee, Jr., et al.; 1998).

        USP 4,703,650 (Dosjoub, et al.; 1987), incorporated in its entirety by reference

herein, discloses a circuit for coding the value of two variables measured in a tire, and a

device for monitoring tires employing such a circuit. The coding circuit comprises an

20   astable multivibrator which transforms the measurement of the variables, for instance

pressure and temperature, into a time measurement. The astable multivibrator delivers a

pulse signal whose pulse width is a function of the temperature and the cyclic ratio of which

is a function of the pressure.

        USP 5,054,315 (Dosjoub; 1991), incorporated in its entirety by reference herein,

25   discloses a technique for coding the value of several quantities measured in a tire. As

disclosed therein:

        "Coding of the value of any number of quantities measured in a tire, for

        example its pressure and its temperature, is carried out using a ratio of time

        intervals TP/Tr, Tt/Tr. This frees the device from the effect of the time shift

30   of the modulation system, the time shift affecting simultaneously the

        numerator and the denominator of said ratio." (Abstract)

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French Patent No. 2,764,977 (Michel; 1998), incorporated in its entirety by reference herein, discloses a transponder (1, see Fig. 1) comprising an integrated circuit (10), with external communication means (antenna coil 11, microprocessor 13), memory (14), rectifier (12), and means (20, 30, 40, 50) for detecting the magnitude of a physical effect, such as

5   temperature. The transponder may be passive, powered by a signal received by the antenna coil and rectified by the rectifier. Various embodiments of detecting means are described (Figures 2, 3, 4), which generally store detection results in memory for possible processing, and for subsequent transmission via the antenna coil which is modulated by the microprocessor.

10   European Patent No. 0,583,690 (1994) and its U.S. equivalent: USP 5,418,358 (1995) (Bruhnke et al.), incorporated in its entirety by reference herein, discloses a chip card with a field strength detector (4) having a switch (T1) and load (R1), to limit damping to the measurement cycle. The "chip card" constitutes a type of passive transponder as described hereinabove. The functions of the chip card which have a high energy requirement to

15   implement them (e.g., measurement operations, EEPROM programming, operation of the field strength detector) are only implemented when the detector has detected a sufficient field strength. The field strength detector consists of a switch and load in parallel to the antenna coil. Data to be transmitted are passed from a user part (3) to a transmission and reception stage (2) which then controls the damping of the reception [antenna] coil (1). A "MOD"

20   signal to the switch (T1) ensures that the field strength detector load (R1) is periodically switched parallel to the reception coil (1) instead of continuously. Furthermore, a controller (REG) prevents the switch from being closed or remaining closed by not passing the MOD signal to the switch if the supply voltage drops below a predetermined value.

European Patent No. 0,473,569 (1992) and its U.S. equivalent: USP 5,345,231 (1994)

25   (Koo et al.), incorporated in its entirety by reference herein, discloses a contactless inductive data-transmission system providing bidirectional signal transfer between a sending and receiving station and one or more batteryless transponders [passive]. A high-frequency signal from the sending and receiving station is pulse width modulated for data transmission to a transponder and provides a system clock, which is extracted in both the sending and receiving

30   station and in the transponder for synchronization, and provides the electrical power for operation of the transponder. The pulse width modulated signal is demodulated in the transponder for triggering a response, wherein a modulating signal is applied by load

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modulation using a modulation transistor (53 in Fig. 8) to switch in and out at least a portion (54) of a coil forming the inductive antenna (10) as an inductive load, to form an information-carrying load-modulated (AM or amplitude modulated) high-frequency signal, which is demodulated in the sending and receiving station.

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SUMMARY OF THE INVENTION

A radio-frequency (RF) transponder comprises circuitry capable of transmitting information unique to an object with which the transponder is associated to an external reader/interrogator. Additionally, one or more transponder sensors (transducers) provide
5   real-time parameter measurement at the transducer location. These measurements are transmitted to the external reader/interrogator, in the form of data in a data stream, on a signal which is output by the transponder, such as by impressing (modulating) the data stream onto an RF signal transmitted by the transponder to the external reader/interrogator.

10   Typically two real-time parameters are measured: pressure and temperature. Pressure is preferably measured by a separate ("off-chip") pressure sensor, which is of a type that varies its capacitance value in a known way, such as a polynomial, or preferably as a substantially linear function of ambient pressure. Preferably, the temperature sensor is embedded ("on-chip") in the IC chip of the transponder and disposed so as to be subject to
15   substantially the same ambient temperature as the pressure sensor so that a true, temperature-compensated pressure can readily be calculated.

The RF signal transmission is typically produced by modulating the RF signal received by a transponder antenna system. According to an aspect of the invention, the RF modulation is achieved by modulating a load across the transponder antenna system.

20   According to a feature of the invention, the magnitude of the modulation load is set according to programmable trim settings, stored in the transponder (e.g., in an EEPROM), which are set to optimize the signal modulation for the individual transponder properties and for the expected transponder operating conditions. This programmable load comprises a plurality of first transistors, a corresponding plurality of second transistors, and control logic
25   for connecting selected ones of the first and second transistors to the antenna system. The transistors can be selected so that the variation is accomplished in binary steps.

According to a feature of the invention, a power supply and level shifters are connected to the modulating load, wherein voltage changes of the power supply dynamically vary the magnitude of the programmable load in proportion to power available in the
30   transponder. Alternatively, the power supply and level shifters are connected to the programmable load, thereby combining the dynamic and the programmable load variation.

According to a feature of the invention, the RF signal modulation is controlled by a phase-shift-keyed signal, formed in a gate by logically combining a system clock signal and the data stream. A circuit is provided for delaying the system clock signal in order to synchronize the system clock signal with the data stream. The modulation signal is blocked by a power-on reset signal, thereby preventing any modulation of the antenna system if the power derived from the RF signal received by the antenna system is too low to provide transponder power adequate for stable transponder operation including RF signal modulation.

Other objects, aspects, features and advantages of the invention will become apparent from the description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference will be made in detail to preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. The drawings are intended to be illustrative, not limiting. Although the invention will be described in the context of these preferred embodiments, it should be understood that it is not intended to limit the spirit and scope of the invention to these particular embodiments.

Certain elements in selected ones of the drawings may be illustrated not-to-scale, for illustrative clarity.

Often, similar elements throughout the drawings may be referred to by similar references numerals. For example, the element 199 in a figure (or embodiment) may be similar in many respects to the element 299 in an other figure (or embodiment).

Such a relationship, if any, between similar elements in different figures or embodiments will become apparent throughout the specification, including, if applicable, in the claims and abstract.

In some cases, similar elements may be referred to with similar numbers in a single drawing. For example, a plurality of elements 199 may be referred to as 199a, 199b, 199c, etc.

The cross-sectional views, if any, presented herein may be in the form of "slices", or "near-sighted" cross-sectional views, omitting certain background lines which would otherwise be visible in a true cross-sectional view, for illustrative clarity.

The structure, operation, and advantages of the present preferred embodiment of the

invention will become further apparent upon consideration of the following description taken in conjunction with the accompanying drawings, wherein:

Figure 1 is a generalized diagram of an RF transponder system comprising an external reader/interrogator and an RF transponder within a pneumatic tire, according to the prior art;

Figure 2 is a block diagram of major components of an RF transponder, according to a previous model of the invention;

Figure 3 is a schematic diagram of major portions of the RF transponder of Figure 2, according to a previous model of the invention;

Figure 3A is a schematic diagram of a portion of the RF transponder of Figure 2, according to a previous model of the invention;

Figure 3B is a schematic diagram of a portion of the RF transponder of Figure 2, according to a previous model of the invention;

Figure 3C is a diagram of a memory space within the RF transponder of Figure 2, illustrating how data may be arranged and transmitted, according to a previous model of the invention;

Figure 3D is a plot of transponder readings versus transponder power for the RF transponder of Figure 2, according to a previous model of the invention;

Figure 4A is a block diagram of major components of an RF transponder, according to the invention;

Figure 4B is a diagram of a memory space within the RF transponder of Figure 4A, illustrating how data may be arranged and transmitted, according to the invention;

Figure 5 is a schematic diagram of a variable modulation portion of the RF transponder of Figure 4A, according to the invention; and

Figure 5A is a schematic diagram of an exemplary circuit in a control logic portion of the circuit of Figure 5, according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

As mentioned hereinabove, it is an aspect of the present invention to provide a system for monitoring vehicle tire pressure and warning the driver when a low tire inflation pressure condition occurs.

Figure 1 illustrates an RF transponder system 100 of the prior art, comprising an RF

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(radio frequency) transponder 102 disposed within (e.g., mounted to an inner surface of) a pneumatic tire 104. (An antenna, not shown, is mounted within the tire 104 and is connected to the transponder 102.) The transponder 102 is an electronic device, capable of transmitting an RF signal comprising unique identification (ID) information (e.g., its own

5 serial number, or an identifying number of the object with which it is associated -in this example, the tire 104) as well as data indicative of a parameter measurement such as ambient pressure sensed by a sensor (not shown) associated with the transponder 102 to an external reader/interrogator 106. The external reader/interrogator 106 provides an RF signal for interrogating the transponder 102, and includes a wand 108 having an antenna

10 110, a display panel 112 for displaying information transmitted by/from the transponder 102, and controls (switches, buttons, knobs, etc.) 114 for a user to manipulate the functions of the reader/interrogator 106. Although shown as a hand-held device, the reader/interrogator may be an electronic unit mounted in a vehicle (not shown). The present invention is directed primarily to implementing an RF transponder.

15   As is known, the ID and/or parameter measurement information may be encoded (impressed) in a variety of ways on the signal transmitted by the transponder 102 to the reader/interrogator 106, and subsequently "de-coded" (retrieved) in the reader/interrogator 106 for display to the user. The RF transponder 102 may be "passive", in that it is powered by an RF signal generated by the external reader/interrogator 106 and emitted by the

20 antenna 108. Alternatively, the RF transponder 102 may be "active", in that it is battery-powered. Transponder systems such as the transponder system 100 described herein are well known.

         Commonly-owned, copending PCT Publication No. WO99/52723 filed 14 April 1998 by Pollack, Brown, Black, and Yones, incorporated in its entirety by reference herein,

25 discloses a transponder, particularly a "passive" transponder which derives its operating power from an external radio frequency (RF) source, and which is associated with a pneumatic tire for use in tire identification and transmission of pressure and/or temperature data.

         The aforementioned PCT Publication No. WO99/52723 discloses a transponder

30 which is a previous model (model number "3070C") of the transponder of the present invention. Since the present invention involves commonalities with, as well as

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improvements upon the previous model, relevant portions of the previous model will be described hereinbelow, with reference to Figures 2, 3, 3A, 3B and 3C.

Figure 2 is a block diagram of the model 3070C RF transponder 200 (compare 102), illustrating the major functional components thereof. This exemplary system is described as

5   an embodiment which preferably measures pressure and temperature, but it is within the scope of the invention to include measurement of other parameters which employ suitable sensors.

The transponder 200 is preferably implemented on a single integrated circuit (IC) chip shown within the dashed line 202, to which are connected a number of external

10   components. Other dashed lines in the figure indicate major functional "blocks" of the transponder 200, and include a transponder "core" 204 and a sensor interface 206. The components external to the IC chip 202 include an antenna system 210 comprising an antenna 212 and typically a capacitor 214 connected across the antenna 212 to form an L-C resonant tank circuit, an external precision resistor (Rext) 216, an external pressure-sensing

15   capacitor (C_p) 218, and an optional external maximum temperature measurement switch (MTMS) 220. The antenna 212 may be in the form of a coil antenna, a loop antenna, a dipole antenna, and the like. Alternatively, the signal output by the transponder may be provided on a transmission line. For some of these antenna embodiments (e.g., a loop antenna), the capacitor 214 may be omitted since it would not be of benefit in tuning such an

20   antenna system. In the main hereinafter, a transponder having a coil antenna is described.

The pressure-sensing capacitor C_p is preferably a rugged, low temperature coefficient, sensor with a capacitance versus pressure response having good sensitivity and linearity in the pressure range of interest. An example is an all-silicon "touch mode" capacitive pressure sensor such as are known in the art, and mentioned hereinabove.

25   The transponder core 204 includes interface circuitry 222 for processing an RF signal, such as a 125 kHz (kiloHertz) un-modulated carrier signal received by the antenna 212, for rectifying the received RF signal, and for providing voltages for powering other circuits on the IC chip 202. For example, the interface circuitry provides a regulated supply voltage (Vdd) of 2.5 volts, and a temperature-independent bandgap voltage (Vbg) of 1.32

30   volts. The provision of various supply and reference voltages for the transponder circuitry are described in greater detail hereinbelow, with reference to Figure 3B. The interface

circuitry 222 also provides the received RF signal, preferably at the input frequency (Fi) it is received, to a clock generator circuit 224 which generates clock signals in a known manner for controlling the timing of other circuits on the IC chip 202, as well as the output frequency (Fc) of a signal which is transmitted by the transponder 200 to the external

5   reader/interrogator (e.g., 106).

A timing generator/sequencer circuit 226 receives the clock pulses from the clock generator circuit 224 and processes (e.g., divides) the clock pulses to generate timing windows (W_T and W_P, described hereinbelow) for predetermined periods of time (t_T and t_P, respectively) during which parameter (e.g., temperature and pressure) measurements are

10   made. The timing windows W_T and W_P may either be of substantially equal duration or of unequal duration. The timing generator/sequencer circuit 226 also controls the timing and sequence of various functions (e.g., pressure measurement and capture, temperature measurement and capture, described in greater detail hereinbelow) performed in the sensor interface 206, and is preferably implemented as an algorithmic state machine (ASM).

15   The transponder core 204 further includes a register/counter circuit 230 which includes a temperature register 232 (e.g., 12-bit) and a pressure register 234 (e.g., 12-bit) for capturing and storing temperature and pressure measurements (counts), respectively, and a block 236 of addressable memory (e.g., 120-bit), which includes an EEPROM array. The registers 232 and 234 and EEPROM array 236 are shown in a dashed line 238 representing

20   a block of addressable memory on the IC chip 202.

The register/counter circuit 230 also includes a multiplexer and column decoder 240, as well as a row decoder 242 for controlling the sequence in which signals (i.e., data) are output on a line 244 to a modulation circuit 246 which, via the interface circuitry 222, communicates selected measured tire operating characteristics in a data stream via the

25   antenna system 210 to an external reader/interrogator (e.g., 106).

The transponder core 204 also includes a baud rate generator 248 which controls the rate at which modulating information (e.g., the temperature or pressure measurement) is applied to the modulation circuit 246. The baud rate generator 248 also provides a data carrier clock controlling the output frequency Fc of the transponder and a data rate clock

30   controlling a rate at which the data stream including measurements, calibration information, identification, etc. is modulated onto the transponder 200 output carrier signal.

The sensor interface 206 includes a circuit 250 for generating an output current I(T)/N on a line 251 which is related to a predictable characteristic voltage of a temperature-sensitive component (e.g., Vbe of a transistor Q1, described hereinbelow) which is superimposed on the external resistor (Rext) 216. The output current I(T)/N on the line 251

5   is provided to a relaxation oscillator 252. In general terms, the relaxation oscillator 252 oscillates at a frequency controlled by a rate of voltage change (dV/dT) which is a function of the output current I(T)/N on line 251 and of internal capacitances C_{FX1}, C_{FX2} associated with the relaxation oscillator 252 as well as an external capacitance (C_p) 218 that can be switched into the oscillator circuit. An output signal Fosc' from the relaxation oscillator 252

10   is provided on a line 253 which, as will be explained in greater detail hereinbelow, is indicative of both ambient temperature and ambient pressure. As used herein, the term "ambient" refers to the parameter being measured in the vicinity of the transponder 200, or more particularly in the vicinity of the respective sensors associated with the transponder 200. When the transponder 200, 102 is mounted within a pneumatic tire (e.g., 104),

15   "ambient pressure" and "ambient temperature" refer to the pressure and temperature of the inflation medium (e.g., air) within the tire 104.

In operation, an RF signal from an external source (i.e., reader/interrogator, not shown, compare 106) is received by the antenna 212. This RF signal is rectified and used to power the RF transponder 200. Modulating information applied to the modulation circuit

20   246 is used to alter characteristics of the antenna system 210 (e.g., impedance, resonant frequency, etc.). These alterations are sensed by the external reader/interrogator 106 and are decoded, providing communication of temperature and pressure information back from the RF transponder 200 to the external reader/interrogator 106.

The timing generator/sequencer circuit 226 controls when the external pressure-

25   sensing capacitance (C_p) 218 is included in the generation of a signal at frequency Fosc' which is output by the relaxation oscillator 252, and also controls the capturing of the pressure and temperature counts via the data capture circuit 254. For example, to measure temperature, the temperature-sensitive current I(T) passes through the internal oscillator capacitors (C_{FX1} and C_{FX2}), but the pressure-sensing capacitor (C_p) 218 is disconnected from

30   (not included in) those capacitances. This means that the frequency Fosc' of the oscillator output signal seen on line 253 is a function of temperature alone. When the pressure-

15

sensing capacitor (C_p) 218 is "switched in", then the output frequency Fosc' of the oscillator 252 on the line 253 will, as explained in greater detail hereinbelow, be a function of both pressure and temperature. As described in greater detail hereinbelow, an algorithm is employed in the reader/interrogator 106 to extract a "pressure-only" reading from the

5   pressure-temperature measurement.

It should be noted that references made herein to "pressure readings", "pressure counts", "pressure response", "pressure register" and the like generally refer to "pressure" as measured by this transponder technique which actually produces a hybrid pressure-temperature reading. When this hybrid reading has been processed to remove its

10   temperature component, the reading will be referred to as a "pressure-only" reading.

As controlled by the timing generator/sequencer circuit 226, the data capture circuit 254 directs the relaxation oscillator output signal Fosc' either to the temperature register 232 via line 255 or to the pressure register 234 via line 257, depending upon whether temperature or pressure is being measured. Counters convert the oscillator frequency Fosc'

15   into counts which are stored in the registers 232, 234. The timing "window" provided by the timing generator/sequencer circuit 226 has a known, controlled duration. As a result, the count remaining in (captured by) the respective temperature or pressure register (232, 234 respectively) when the timing window "closes" is a function of (proportional to) the oscillation frequency Fosc' of the relaxation oscillator 252, and therefore a function of

20   temperature or pressure, whichever is being measured during that timing window.

The EEPROM array 236 is used to hold calibration constants that the reader/interrogator (e.g., 106) uses to convert temperature and pressure counts (N_T and N_P, respectively, described in greater detail hereinbelow) into temperature and pressure readings which can be displayed (e.g., via display 112) to a user. The EEPROM array 236 can also

25   store the ID of the transponder, calibration data for the transponder, and other data particular to the given transponder.

Figure 3 is a more-detailed schematic diagram 300 of several of the components of the transponder 200 of Figure 2, primarily those components described hereinabove with respect to the sensor interface section 206 of Figure 2.

30   In this schematic diagram 300, conventional circuit symbols are employed. For example, lines which cross over one another are not connected to one another, unless there

is a "dot" at their junction (cross-over), in which case the lines are connected with one another. Conventional symbols are employed for transistors, diodes, ground connections, resistors, capacitors, switches, comparators, inverters, and logic gates (e.g., "AND", "NAND", "OR", "NOR").

5   The circuit is described in terms of a CMOS embodiment, wherein "P" followed by a number (e.g., "P1") indicates a PMOS (P-channel) transistor and "N" followed by a number (e.g., "N1") indicates an NMOS (N-channel) transistor. CMOS transistors are of the FET (field effect transistor) type, each having three "nodes" or "terminals" - namely, a "source" (S), a "drain" (D), and a "gate" (G) controlling the flow of current between the

10   source and the drain. In the description that follows, it will be evident that a number of the PMOS and NMOS transistors are "diode-connected", meaning that their drain (D) is connected to their gate (G). The general theory of operation of transistors, particularly CMOS transistors, is well-known to those having ordinary skill in the art to which the present invention most nearly pertains.

15   As will be evident from the description that follows, a number of the CMOS transistors are connected in a "current-mirroring" configuration. The concept of current-mirroring is well known, and in its simplest form comprises two similar polarity transistors (e.g., two PMOS transistors) having their gates connected with one another, and one of the pair of transistors being diode-connected. Current-mirroring generally involves causing a

20   current to flow through the diode-connected transistor, which results in a gate voltage on the diode-connected transistor required to produce that current. Generally, the gate voltage of the diode-connected transistor is forced to become whatever voltage is necessary to produce the mirrored current through that transistor. Since the diode-connected transistor, by definition, has no gate current, by applying the gate voltage of the diode-connected transistor

25   to any other identically-connected transistor, a mirrored-current will flow through the identically-connected transistor. Typically, the current-mirroring transistors all have the same physical area, in which case the mirrored current will be essentially the same as the current which is being mirrored. It is also known to produce a mirrored current which is either greater than or less than the current being mirrored by making one of the transistors

30   physically larger or smaller (in area) than the other. When such identically-connected transistors having different areas are connected in a current-mirroring configuration, their

scaled (larger or smaller) areas will produce correspondingly scaled (larger or smaller) currents.

In the main hereinafter, the numerous connections between the various components of the circuit are clearly illustrated in the figure, and the descriptive emphasis is on the various functions of and interactions between the various components of the circuit rather than on reciting (ad nauseam) each and every individual connection between the various components, all of which are explicitly illustrated in the figure.

The antenna system 210 comprises a coil antenna 212 and an optional capacitor 214 (connected across the antenna 212 to form an L-C resonant tank circuit) providing an alternating current (AC) output to a full-wave rectifier circuit 302.

The full-wave rectifier circuit 302 (compare 222) comprises two PMOS transistors and two diodes, connected in a conventional manner, as shown, and outputs a full wave rectified direct current (DC) voltage on a line 303. A capacitor 304 is connected between the line 303 and ground to "smooth out" (filter) variations ("ripple") in the full wave rectified DC voltage on the line 303. The voltage on the line 303 thus becomes a usable voltage for the remaining components of the transponder - in this case, a positive supply voltage Vcc on the line 303.

A temperature-sensing circuit 306, corresponding approximately to the base-emitter voltage-to-current converter 250 of Figure 2, is connected between the line 303 (Vcc) and ground, and includes four CMOS transistors labeled P1, P2, N1 and N2 and a lateral bipolar transistor labeled Q1, and is connected to the external resistor 216 (Rext). The transistors P2 and N1 are diode-connected, as illustrated. The two transistors P1 and P2 are connected in a current-mirroring configuration, and the two transistors N1 and N2 are also connected in what can generally be considered to be a current-mirroring configuration. The source (S) of the transistor N1 is connected via the transistor Q1 to ground, and the source of the transistor N2 is connected via the external resistor (Rext) 216 to ground.

As will become evident, the ability of the temperature-sensing circuit 306 to produce a signal (i.e., a current) that is proportional to a sensed ambient temperature (e.g., within the tire with which the transponder is associated) is largely dependent on the characteristic that the base-emitter voltage of the transistor Q1 is a highly predictable and repeatable function of temperature. The resistor (Rext) 216 is an external, precision, reference

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resistor, whose value is substantially independent of temperature (as contrasted with the temperature dependency of the transistor Q1). A suitable value for the resistor (Rext) 216 is, for example, 20.5 kilohms or 455 kilohms.

The transistor N2 is connected between the transistor P2 and the external resistor
5   216 (Rext) in a "source-follower" mode. As a voltage is impressed on the gate (G) of the transistor N2, its source voltage will "follow" its gate voltage (minus an inherent voltage drop (Vgs) between its gate and its source).

As current flows through the transistor N1, its gate voltage will be offset by its gate-source voltage drop (Vgs) above the emitter voltage at the transistor Q1. Since the
10   transistors N1 and N2 are essentially identical, with the same current flowing through each of the two transistors N1 and N2, they will have identical gate-source voltage drops (Vgs). As a result, the voltage at the source of the transistor N2 across the external resistor 216 (Rext) will be essentially identical to the voltage at the emitter of the transistor Q1. Hence, applying Ohm's law (E=IR, or I=E/R), the current through the external resistor 216 (Rext)
15   will equal the emitter voltage of the transistor Q1 divided by the resistance of the external resistor 216 (Rext).

In normal operation, all of the current flowing through the external resistor (Rext) 216 flows through the source of the transistor N2 and, consequently, through the diode-connected transistor P2. By a current-mirroring connection, the current through the
20   transistor P2 is replicated (mirrored) in the transistor P1. This ensures that the current flowing through the transistors N1 and N2 will be the same, at all times, which further helps to ensure that the emitter voltage at the transistor Q1 and the voltage across the external resistor (Rext) 216 are identical, independent of voltage and process variations. As mentioned hereinabove, the transistors N1 and N2 are connected in what can generally be
25   considered to be a current-mirroring configuration. However, since they are not strictly identically connected, their function in the circuit 306 is principally for "matching" Q1 and Rext.

In essence, the circuit 306 ensures that the current I(T) flowing through the external resistor (Rext) is predictable, and is a function of the absolute temperature (T) of the
30   transistor Q1. As described in greater detail hereinbelow, this temperature-dependent current I(T) flowing through the external resistor (Rext) 216 is mirrored to a relaxation

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oscillator (312, described hereinbelow) to provide a signal indicative of the temperature of

the transistor Q1 to the external reader (106, Figure 1). As described in greater detail

hereinbelow, the output frequency Fosc' of the relaxation oscillator 312 will be a function of

the absolute temperature (T) of the transistor Q1.

5   At this point, it is useful to note that it is essentially the transistor Q1 that is being

employed as the temperature-sensing element of the overall transponder circuit. The

transponder circuit advantageously employs an inherent characteristic of such a transistor

implemented in CMOS technology that the base-emitter voltage of the transistor Q1 will

vary by a predictable amount of -2.2 mv/°C (millivolts per degree Celsius).

10   It should be noted that the transponder of the present invention is described in terms

of a "passive" device, relying on RF energy being supplied to it by an external source (106,

Figure 1) to power up its circuitry. However, it is within the scope of this invention that the

transponder contains its own power supply, such as in the form of a battery. In either case,

when first powering up circuitry such as described with respect to the temperature-sensing

15   circuit 306, it is important to ensure that they "ramp up" to their normal operating state from

their quiescent state in a reliable and predictable (controlled) manner. To this end, two lines

305 and 307 are illustrated which are connected between the temperature-sensing circuit 306

and a "startup" circuit 308.

        The startup circuit 308 (also part of the base-emitter voltage-to-current converter 250

20   of Figure 2) is connected between the supply voltage (Vcc) on the line 303 and ground, and

serves two main purposes: (i) to get current flowing in the temperature-sensing circuit 306

when the transponder (200) first starts up from a powered down state; and (ii) to mirror and

convert the current flowing through the transistor P2 from a supply-referenced current to a

ground-referenced current.

25   Startup is initiated by the transistor P3. The transistor P3 is fabricated to have high

channel resistance so as to function in a "weak pull-up" mode. With its gate connected to

ground, it will always be "on", and will behave essentially like a resistor having a high

resistance (e.g., > 1 mega-ohm).

        Since, at startup, no current flows elsewhere in the circuit, the transistor P3 operates

30   to pull the gate of the transistor N3 towards the supply voltage (Vcc), thereby turning the

transistor N3 "on", which effectively connects the grounded source or transistor N3 to its

drain (D) which, in turn, grounds the gates of transistors P1, P2, and P4, and also grounds the drain of diode-connected transistor P2. This causes current to flow through the transistor P2 of the temperature-sensing circuit 306 into the drain of the transistor N3. Since the transistors P1, P2 and P4 are current-mirror connected (via the "Pbias" line 305),

5   the current now flowing through transistor P2 will be mirrored in the transistors P1 and P4. As current flows through the transistor P4 into the diode-connected transistor N5, a current-mirroring connection between the transistors N4 and N5 causes a corresponding current to flow through the transistor N4, thereby pulling the gate of transistor N3 to ground, thereby effectively shutting "off" the flow of current through the transistor N3.

10   However, with current now flowing through the current-mirrored transistors P1, P2 and P4, current flowing from the transistor P1 through the diode-connected transistor N1 into the transistor Q1 forces the temperature-sensing circuit 306 to "start up" in its stable operating point state (rather than its zero current state). After startup, the transistor N3 essentially "drops out" of the circuit, having performed its intended function.

15   The transistor N5 is connected in a current-mirroring configuration with the transistor N4 (and, as described hereinbelow, with the transistor N6). Therefore, essentially, with a current equivalent to the current through the external resistor (Rext) 216 flowing through the transistor N5, the same current flows through the transistor N4, thereby establishing a reference voltage (Nbias) on the line 309. The reference voltage (Nbias) on

20   the line 309, as well as a supply voltage (Vdd) on a line 309', are provided to a current scaling circuit 310.

          The supply voltage (Vdd) on the line 309' is provided in any suitable manner, such as a multiple of a bandgap voltage (Vbg) generated in a conventional manner elsewhere on the chip, and its magnitude (e.g., 1.32 volts) should be independent of temperature, such as

25   inherent to the silicon process which is employed in making the chip. The provision of such a stable (e.g., bandgap) voltage (e.g., Vbg) and the supply voltage (e.g., Vdd) derived therefrom is well within the purview of one having ordinary skill in the art to which the present invention most nearly pertains, and is described in greater detail hereinbelow with respect to Figure 3B.

30   The current scaling circuit 310 (also part of the base-emitter voltage-to-current converter 250 of Figure 2) is constructed in the following exemplary manner. The sources

of the transistors P5 and P6 are connected to supply voltage Vdd. The gate of a transistor

N6 receives the reference voltage (Nbias) on the line 309. The transistor N6 is connected in

a current-mirroring configuration with the transistor N5 (as well as with the aforementioned

transistor N4) and will therefore mirror the flow of current I(T) through the transistors N4

5   and N5. Consequently, the flow of current through the diode-connected transistor P5 will

mirror the flow of current through the transistors N4, N5 and N6.

The transistors P5 and P6 are connected in a current-mirroring configuration, but are

fabricated (using conventional CMOS fabrication techniques) such that current flowing

through the transistor P6 is scaled up or down by a ratio (N) of the physical area of the

10   transistor P5 to the physical area of the transistor P6. For example, if the transistor P6 is

smaller in size than the transistor P5 (i.e., the transistor P5 is "N" times larger in area than

the transistor P6), then the current flowing through the transistor P6 will be commensurately

(N times) smaller than the current flowing through the transistor P5. Thus, the "scaled"

current flowing through the transistor P6, is labeled "I(T)/N" in the figure, and is provided

15   on a line 311 (compare 251) to a relaxation oscillator circuit 312 (compare 252). It is well

known that the ratio of the currents between the transistors P5 and P6 can readily be

established by conventional circuit processing techniques, such as by simply making one of

the transistors larger than the other, or by implementing a one of the two transistors as the

aggregate of two or more same-size transistors so that their aggregate area is larger than the

20   area of the other of the two transistors.

The relaxation oscillator circuit 312 (compare 252) is of fairly conventional design,

and includes a measurement switching circuit 315 at the "front end" of a set-reset circuit 314

comprising two phase paths 314a, 314b. This circuit 315 comprises a pair of

complementary transistors P7 and N7 connected to a charged side of a measurement

25   capacitor C_{FX1} at the front end of a one phase path (ϕ1) 314a; and another pair of

complementary transistors P8 and N8 connected to a charged side of another measurement

capacitor C_{FX2}, plus a switch 350 to add another measurement capacitor C_P, all at the front

end of another phase path (ϕ2) 314b.

Connected as illustrated, for a given pair of transistors (e.g., P7 and N7), when their

30   common gate voltage is high (i.e., towards positive supply) their output (e.g., to phase path

314a) will be grounded (connected to ground and isolated from current I(T)/N on line 311),

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and when their common gate voltage is low, their output will provide the current I(T)/N flowing on the line 311 to a respective one of the phase paths (e.g., 314a) of the relaxation oscillator 312. As is known for circuitry such as the relaxation oscillator 312, when the common gate voltage of a one of the pairs of transistors (e.g., P7 and N7) is high, the

5   common gate voltage of the other of the pairs of transistors (e.g., P8 and N8) will be low, and vice-versa. In this manner, each phase path 314a and 314b has a duty cycle (i.e., its "on" time), which may be the same as or may be different than the duty cycle of the other phase path 314b and 314a, respectively. Thus, each pair of transistors (e.g., P7 and N7) may be considered to be an "input switch" to its respective phase path (e.g., 314a).

10   Each phase path 314a and 314b of the relaxation oscillator 312 has a comparator 316a and 316b, respectively, at its input, and has a fixed-value capacitor C_{FX1} and C_{FX2}, respectively, connected between the negative (-) input of the comparators 316a and 316b and ground. The capacitors C_{FX1} and C_{FX2} have exemplary capacitance values of 2-5 pf (picofarads) and 2-5 pf, respectively, and are preferably implemented as equal-valued "on-

15   chip" devices, such as poly-to-poly capacitors exhibiting a low temperature coefficient (e.g., less than 20ppm). The positive (+) inputs (terminals) of the comparators 316a and 316b are tied together and are set to a reference threshold voltage Vbg, such as 1.32 volts, which is independent of temperature.

A "NOR" logic gate 318a and 318b is connected at the output of each phase path

20   314a and 314b, respectively, and the two NOR gates 318a and 318b are cross-connected to form a latching circuit having an output on a line 319a and 319b. The cross-connected NOR gates 318a and 318b are thus capable of functioning as a flip flop, or an RS (re-set/set) latch.

When the common gate voltage of one of the input switches (e.g., P7 and N7) is high, the respective capacitor (e.g., C_{FX1}) for that phase path (e.g., 314a) is grounded

25   (shorted out, caused to be devoid of charge). Conversely, when the common gate voltage of one of the input switches (e.g., P7 and N7) is low, the scaled current I(T)/N from line 311 is applied to (allowed to flow into) the respective capacitor (e.g., C_{FX1}) for that phase path (e.g., 314a), and the capacitor begins to charge (acquire an increasing voltage across the capacitor). When the voltage across the capacitor C_{FX1}/C_{FX2} reaches the comparator

30   reference voltage Vbg the output of the comparator 316a/316b goes low and changes the state of the output of the latch 318a/318b on the line 319a/319b. In this manner, the

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relaxation oscillator 312 will oscillate at a frequency Fosc determined by the rise time of the

capacitors C_{FX1} and C_{FX2} and, importantly, by the scaled current $I(T)/N$ being supplied to the

capacitors C_{FX1} and C_{FX2}. With greater current $I(T)/N$ being supplied, the voltages of the

capacitors C_{FX1} and C_{FX2} will rise faster, crossing the threshold voltage faster, and causing

5   the relaxation oscillator 312 to oscillate faster, thereby increasing the frequency Fosc of the

signal on the line 319a. The signal on the line 319a is inverted by an inverter 320, as

shown, to provide a signal of frequency Fosc' on the line 321.

As described in greater detail hereinbelow, the oscillator 312 is controlled to run in

two mutually-exclusive modes, a temperature-sensing mode (between times t0 and t1) and a

10   pressure-sensing mode (between times t1 and t2), as controlled by the timing

generator/sequencer 226. The frequency of the oscillator output signal Fosc (and Fosc')

will be different in each of these two modes.

GENERATING TEMPERATURE AND PRESSURE READINGS

In the exemplary context of the transponder 200 being associated with a pneumatic

15   tire, it is principally desirable to determine the pressure within the pneumatic tire. For

example, a typical passenger vehicle tire may be properly inflated at about 32 psi (about 221

kPa). Since tire inflation pressures are normally specified as "cold" pressures (pressure

measured when the tire is not heated by operation), and since a monitoring device will be

reporting pressures measured in tires which are most likely in use and therefore "hot", it is

20   secondarily desirable to determine the temperature of the inflation medium (e.g., air) within

the pneumatic tire. Utilizing the temperature measurement, a monitoring system (e.g., 106)

can, for example, convert the measured pressure to a "cold" pressure with simple

calculations based on the ideal gas law ($PV = \mu RT$). This "cold" pressure could be

considered a "temperature-independent" pressure, which is also an indication of the mass of

25   air contained by the tire. With reference to the transponder 200, the hybrid "pressure"

measurement it produces must be converted (by different calculations detailed hereinbelow)

to a true pressure-only measurement before it can be used in such gas-law calculations.

It is, for example, estimated that an approximate 10% decrease in fuel consumption

could be realized if the pneumatic tires on vehicles were operated at their specified pressure.

30   Although vehicle fleet operators are typically sensitive to this issue, and check and adjust

tire pressure frequently, the average operator of a passenger vehicle is often less inclined to

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keep an eye on their tire pressure until, for example, the tire is visibly flattened out. In such cases, an LCD (liquid crystal display) readout or the like on the dashboard of a car could provide dynamic tire inflation information to the operator of a vehicle, the pneumatic tires of which are equipped with a transponder such as the one described herein. Of no less

5   significance is the emergence of "run-flat" tires being marketed by various tire manufacturers. The Goodyear EMT (extended mobility technology) series of tires is an example of a "run-flat" tire, an overall purpose of which is to allow a driver to travel up to 50 miles (approximately 120 kilometers) on a deflated ("flat") tire, at "reasonable" operating speeds (e.g., 60 miles per hour, or 144 kilometers per hour), while maintaining

10   normal control over the vehicle. Such run-flat tires are generally well known, and do not form a portion of the present invention, per se. When running "flat" on a run-flat tire, it is particularly important that the driver be alerted to the fact that he or she is operating the vehicle on "borrowed time" as indicated, principally, by an indication, whether visual or audio (e.g., a beep) that the tire is indeed "flat" and needs to be repaired or replaced at his

15   or her earliest convenience (and before the run-flat mileage limit).

By allowing the relaxation oscillator 312 to run, the frequency of its output signal Fosc (and Fosc') will be a function of the absolute temperature of (sensed by) the transistor Q1. This is true in both the temperature-sensing mode and the pressure-sensing mode of operation.

20   In the temperature-sensing mode, and in the case that the capacitance values for C_{FX1} and C_{FX2} are equal, which is preferred, the relaxation oscillator 312 will have a symmetrical (balanced, 50%) duty cycle. In the pressure-sensing mode, the pressure-sensing capacitor (C_P) 218 is switched by a semiconductor switch 350 across C_{FX2}, which changes the duty cycle and output frequency Fosc (and Fosc') of the relaxation oscillator 312.

25   In the temperature-sensing mode, only the fixed capacitors C_{FX1} and C_{FX2} are being alternately charged (and discharged) resulting in a 50% duty cycle with a period proportional to ambient temperature. In the pressure-sensing mode, the pressure-sensing capacitor (C_P) 218 is switched into phase path 314b of the oscillator 312. Thus, for a given temperature, for the first half of the oscillator period the phase path 314a behaves in the

30   same manner as in the temperature-sensing mode, and for the second half of the oscillator period the phase path 314b behaves in a manner that is proportional to the capacitance value

of the fixed capacitor C_{FX2} plus the capacitance value of the pressure-sensing capacitor (C_P) 218. This, in effect, slows down the oscillator and changes its duty cycle. The change in the duty cycle is indicative of the ratio of C_P to C_{FX2}. Thus, from the ratio of the two periods (with and without C_P in the circuit, it is straightforward to calculate what the

5   additional capacitance C_P is, hence the sensed pressure. As described in greater detail hereinbelow, the temperature-dependency of the oscillator output in the pressure-sensing mode can be completely eliminated, in a straightforward manner.

The "slowing down" of the oscillator when the pressure-sensing capacitor (C_P) 218 is switched into the oscillator circuit results, inevitably, in there being relatively fewer

10   oscillator output pulses (reduced output frequency) to count during a given pressure-measurement window (e.g., W_P) than during a similar duration temperature-measurement window (e.g., W_T). In other words, a "slowed-down" oscillator will reduce that rate at which counts indicative of the parameter measurement are collected. In order to increase the resolution (quantity) of the counts (N_P) generated during the pressure-measurement

15   window (W_P), it is contemplated that the pressure-measurement window (W_P) can be increased in size (changed in duration) so as to allow for the capture of an appropriate number of pressure counts in the pressure register 234. This can readily be accomplished simply by establishing a larger (than otherwise) value for the time t2 which establishes the end of the pressure-measurement window (W_P) in the pressure-sensing mode (between times

20   t1 and t2), as controlled by the timing generator/sequencer 226. For example, the temperature-measurement window W_T (between times t0 and t1) can be on the order of several ones (e.g., eight) of milliseconds, and the pressure-measurement window W_P can be on the order of tens or dozens (e.g., eighty) of milliseconds. Alternatively, it is contemplated that the scaled current ($I(T)/N$) flowing out of the current scaling circuit 310 to

25   the relaxation oscillator 312 could be increased during the pressure-measurement window (W_P) to increase the fundamental frequency of the relaxation oscillator 312, thereby increasing the overall resolution of the pressure count. This can readily be accomplished, for example in the case of transistor P6 being smaller in size (area) than the transistor P5, simply by switching in a transistor P6' (not shown) in lieu of the transistor P6, the transistor

30   P6' having a larger area than the transistor P6 so that the ratio of the areas of the transistors P5 and P6 is closer to unity (i.e., less scaled down) and the current to the relaxation

oscillator 312, hence its counting rate, is increased. Such switching in of another transistor P6' is readily effected with a switch (not shown) comparable to the aforementioned switch 350 which switches in the pressure-sensing capacitor (C_P) 218. One having ordinary skill in the art to which the present invention most nearly pertains will readily understand how to offset the "slowing down" of the oscillator when the pressure-sensing capacitor (C_P) 218 is switched into the oscillator circuit, in light of the teachings presented herein.

OPTIMIZING PRESSURE-RESPONSIVENESS

Obtaining (and displaying) an accurate pressure reading being of paramount importance when monitoring the pressure of a pneumatic tire, certain parameters of the transponder circuit may be established to maximize its pressure-responsiveness and therefore improve the accuracy of the pressure reading displayed by the external reader/interrogator (e.g., 106).

As described hereinabove, the transponder responds to the changing capacitance of the pressure sensor (C_P) 218 by changing the value of a binary 12-bit word that is transmitted to the external reader/interrogator 106. This binary word is the count of an oscillator frequency during a timing window W_P (between t1 and t2) established by the timing generator/sequencer 226. The pressure response can therefore be described as the change in counts per unit change in capacitance of the pressure-sensing capacitor (C_P) 218.

Pressure-responsiveness (and resolution) of the transponder has been found to be dependent on a number of factors, each of which can be analyzed. For example, it has been determined that:

(a) Increasing the pressure-measurement window W_p to make it larger than the temperature-measurement window W_t will increase the pressure count N_p (and not the temperature count N_T) for a given value of the pressure-sensing capacitor (C_P) 218, to make up for the relatively lower oscillator frequency which occurs during pressure measurement compared to temperature measurement (as detailed hereinabove).

(b) Increasing the scaled current I(T)/N to the oscillator 312 will proportionally increase the pressure count N_P for a given value of the pressure-sensing capacitor (C_P) 218.

(c) Decreasing the values for capacitor(s) C_{FX1} and/or C_{FX2} will proportionally increase the pressure count N_P for a given value of the pressure-sensing capacitor (C_P) 218.

(d) Increasing the scaled current I(T)/N to the oscillator will proportionally increase

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the pressure count N_P (for a given value of C_P) at a greater rate than decreasing the values

for capacitors C_{FX1} and C_{FX2}.

(e) Increasing the scaled current $I(T)/N$ will increase both the pressure counts N_P and

the temperature counts N_T unless the current increase can be made to occur only during the

5   pressure-measurement window W_p.

(f) Decreasing the values for capacitor(s) C_{FX1} and/or C_{FX2} will increase both the

pressure counts N_P and the temperature counts N_T even if only one of the capacitors is

changed.

As a general proposition, increasing the pressure counts N_P is desirable. However,

10   one having ordinary skill in the art to which the present invention most nearly pertains will

readily appreciate that there is a practical upper limit to increasing the pressure counts at a

frequency which may become unacceptably large for the capability of certain circuits of the

IC chip.

MEASURING PARAMETERS

15   Figure 3A illustrates the components involved in the final step of capturing

temperature and pressure measurements in the transponder. The signal Fosc' output by the

relaxation oscillator 312 is provided on line 321 (compare 253) to an input of each of two

AND gates 360 and 362 in the data capture circuit 254. A signal ("Capture Temp") is

provided by the timing generator/sequencer 226 to the other input of the AND gate 360

20   during the temperature-sensing window (W_T) so as to load the temperature register 232 via

line 255 with the count ("data," or "reading") N_T indicative of measured temperature.

Another data signal ("Capture Press") is provided by the timing generator/sequencer 226 to

the other input of the AND gate 362 during the pressure-sensing window (W_P) so as to load

the pressure register 234 with the count ("data," or "reading") N_P indicative of measured

25   pressure. Each of the registers 232, 234 has a counter (not shown) associated with it to

convert the incoming oscillating signal Fosc' to a stored count. The two counts N_T, N_P are

then shifted out of the registers 232 and 234, via the MUX 240, to the modulation circuit

246 described hereinabove.

When the transponder is powered up, temperature and pressure are continuously

30   measured, and these measurements are transmitted back to the external reader/interrogator

106 as data words in a data stream. For example, each of the temperature and pressure

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parameters can be transmitted back to the reader/interrogator 106 as 12-bit data words in selected (known) portions of a larger (e.g., 144-bit) data stream.   One bit in the overall data stream may be dedicated to the state (e.g., "closed" or "open") of the MTMS switch 220. A complete description of an exemplary data stream being transmitted by the transponder to

5   the external reader/interrogator is set forth hereinbelow with reference to Figure 3C.

Temperature is suitably measured by counting the number of cycles output from the oscillator 312 during a fixed time period (window W_T of time from t0 to t1) having a time period t_T. For example, a down-counter (not shown, but associated with the temperature register 232) may be clocked by the oscillator, such that at the end of the window W_T time

10   period t_T, a temperature count N_T is generated. The relationship between temperature count N_T and temperature is substantially linear for the circuitry 300 of this embodiment.

Similarly, pressure can be measured by counting the number of cycles output from the oscillator 312 during a fixed time period (window W_P of time from t1 to t2) having a time period t_P. For example, a down-counter (not shown, but associated with the pressure

15   register 234) may be clocked by the oscillator, such that at the end of the window W_P time period t_P, a temperature count N_P is generated. The relationship between pressure count N_P and pressure is a predictable function of both actual pressure and temperature for the circuitry 300 of this embodiment. As explained hereinbelow, by manipulating the temperature and "pressure" counts (N_T and N_P) this hybrid pressure-temperature value can

20   be used to determine a pressure-only value.

OBTAINING A PRESSURE-ONLY READING AT THE READER/INTERROGATOR

The fundamental frequency of the oscillator 312 is set by parameters in the IC chip (e.g., 202) and, as described hereinabove, is temperature-dependent. Therefore, the

25   pressure response N_P is a function (hybrid) of both temperature and pressure, and the relationship of N_P to C_P is nonlinear. Therefore, using a linear equation for calculating the pressure response would inevitably lead to significant errors over a range of pressures being measured. However, for limited ranges of pressures being measured, for example over a 20 psi (138 kPa) range of pressures, using a linear equation may be acceptable. A better

30   approximation might be obtained using a polynomial equation, but this would complicate the reader/interrogator logic, making for slower response, and would require additional

calibration constants.

An important advantage of using the transponder circuitry described hereinabove is that the relationship of N_T/N_P to pressure sensor capacitance C_P is linear, and requires no temperature compensation term in the equation (algorithm) used by the reader/interrogator

5   106 to calculate pressure, thereby greatly simplifying the design of the reader/interrogator. (This also assumes the use of a pressure sensor (C_P) 218 which has a substantially linear relationship between pressure and capacitance.) This beneficial "ratiometric" relationship is readily demonstrated by the following equations:

Generally,

10    $$\text{count} = \text{counting window time (t)} * \text{frequency (F)}$$

$$F = 1/\text{period}$$

$$\text{Charging time} = V * C / I$$

for a capacitor with capacitance C to be charged to a voltage V with a current I.

Since the period of the relaxation oscillator 312 with output signal of frequency

15   Fosc' is the sum of the charging times for the capacitances in the two phase paths 314a and 314b, the above equations can be manipulated to obtain a general equation for the count from such a relaxation oscillator with capacitances C_{FX1} and C_{FX2}, for example:

$$\text{count} = t/(V*C_{FX1}/I + V*C_{FX2}/I) = t*I/(V*(C_{FX1} + C_{FX2}))$$

Substituting the values for the temperature and pressure counts:

20    $$N_T = (t_T*I(T)/n_T)/(Vbg*(C_{FX1}+C_{FX2}))\qquad\qquad\text{[EQ. A]}$$

$$N_P = (t_P*I(T)/n_P)/(Vbg*(C_{FX1}+C_{FX2}+C_P))$$

where n_T and n_P are values for the scaling factor N in the scaled current $I(T)/N$ which could be different during the temperature and pressure measurement windows, respectively.

25   Dividing equations to obtain N_T/N_P:

$$N_T/N_P = (t_T/t_P)*(n_P/n_T) * (C_{FX1}+C_{FX2}+C_P)/(C_{FX1}+C_{FX2})$$

or

$$N_T/N_P = (t_T/t_P)*(n_P/n_T) * (1 + (C_P/(C_{FX1}+C_{FX2}))\qquad\text{[EQ. B]}$$

Since everything to the right of the equals sign is a defined constant except for the pressure-

30   sensing capacitance C_P, it can be seen that there is a linear relationship between N_T/N_P and C_P (and thus pressure). This means that N_T/N_P is only a function of pressure, and is

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insensitive to temperature or capacitor-charging current variations.

If none of the response optimization steps described hereinabove have been utilized, then the equation EQ. B can be simplified since capacitors C_{FX1} and C_{FX2} have the same value C_{FX}; the measurement windows W_T and W_P have the same time width $t_T = t_P = t_W$ (e.g., 8.192 ms); and the current scaling factors n_T and n_P have the same value N:

$$N_T/N_P = 1+(C_P/2*C_{FX})$$

It can be seen from equation EQ. A that there is already a linear relationship between the temperature count N_T and the current I(T) (which is, in turn, proportional to temperature).

In both of the measurement equations EQ. A and EQ. B it can be seen that linear relationships exist, but the slope and intercept of these equations are complex combinations of multiple parameters which are unique to a given transponder design, and are likely to be different even for each transponder of a given design due to manufacturing variances. In a simple embodiment of this invention, the transponder could transmit only the counts N_T and N_P to a reader/interrogator, and the reader/interrogator would have to use assumed average values for slope and intercept in order to determine temperature and pressure. This could cause significant inaccuracy, so the preferred embodiment as described herein stores calibration constants in the transponder memory (e.g., 236) and transmits these calibration constants with the measurement counts N_T and N_P so that the reader/interrogator (e.g., 106) can accurately calculate temperature and pressure using linear equations customized/optimized for the individual transponder generating the measurements. The linear equations used in the exemplary reader/interrogator (e.g., 106) are of a well-known "point-slope" form:

$$y-y_1 = m(x-x_1)$$

where:

(x_1,y_1) is the defining point; and

m   is the slope.

The slope (m) can be determined from any two points on the line: (x_1,y_1), (x_2,y_2):

$$m = (y_2-y_1)/(x_2-x_1)$$

Substituting for x and y, a specific equation for the temperature response line becomes:

$$N_T- N_{T1} = m_T(T-T_1)$$

Choosing a value such as 25°C for temperature T_1 yields the equation:

$$N_T - N_{T25} = m_T(T-25)$$

Solving for N_T yields the following equation for the temperature response line:

$$N_T = m_T(T-25) + N_{T25}$$

5   wherein the slope m_T of the temperature response line is:

$$m_T = (N_{T2}-N_{T1})/(T_2-T_1)$$

As long as the reader/interrogator "knows" the assumed defining point temperature (e.g.,

25°C), then it will be able to calculate a temperature (T) from a received value of

temperature count N_T using the calibration constants: a defining point temperature count

10   N_{T25} and a slope m_T which are also transmitted to the reader/interrogator. A similar set of

equations can be applied to determine pressure from transmitted pressure (and temperature)

counts and pressure calibration constants. As noted hereinabove, the pressure-only reading

is best determined from a linear equation utilizing a ratio N_T/N_P (temperature count divided

by pressure count) instead of just the pressure count N_P.

15   The calibration constants are determined in a calibration process which includes

exposing each transponder to a set of controlled, known temperature and pressure conditions

and recording the corresponding set of temperature and pressure counts (N_T and N_P)

generated by that transponder. Calculations on these calibration test results determine four

calibration constants which are then stored in the transponder memory (e.g., 236). The four

20   calibration constants are numbers representative of the slope and defining point for a linear

response of temperature versus temperature count N_T, and pressure (only) versus count ratio

N_T/N_P.

GENERATING RELIABLE SUPPLY AND REFERENCE VOLTAGES

                As described hereinabove, the positive (+) inputs (terminals) of the comparators

25   316a and 316b are tied together and are set to a reference "bandgap" voltage Vbg, such as

1.32 volts, which is independent of temperature. As also mentioned hereinabove, the supply

voltage (Vdd) on the line 309' may be provided as a multiple of the reference bandgap

voltage (Vbg) so as to be a stable operating voltage for the current scaling circuit 310 and

the relaxation oscillator 312.

30   Figure 3B illustrates a circuit 370 suitable for generating the supply voltage Vdd. A

temperature-independent calculable bandgap voltage Vbg is readily derived, based on the

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processing techniques employed in fabricating the IC chip, as being inherent to the selected process (e.g., CMOS). This bandgap voltage Vbg is provided to the positive (+) input of an operational amplifier 372, connected as shown, in a feedback loop having gain, to provide supply voltage Vdd as an integral multiple of the bandgap voltage Vbg.

5   **AN EXEMPLARY DATA STREAM**

As mentioned hereinabove, information (data) from the transponder is transmitted to the external reader/interrogator in the form of a data stream, a portion of which is the temperature count N_T, another portion of which is the pressure count N_P, and another portion of which represents the state (e.g., "closed" or "open") of the MTMS switch (220).

10   Remaining portions of the data stream may contain information which is personalized to a given transponder unit such as its ID information (e.g., serial number), calibration constants, and the like.

Figure 3C illustrates an exemplary architecture for information which is stored in memory (e.g., 238) within the transponder 200, as well as a data stream which is

15   transmitted by the transponder 200 to the external reader/interrogator 106. The memory 238 of the transponder core 204 has, for example, a 144-bit address space which includes 119 (one hundred nineteen) bits of programmable memory and one address location dedicated to the state of the MTMS switch 220 - these 120 (one hundred twenty) bits of programmable memory constituting the EEPROM 136 - plus two 12-bit temperature and

20   pressure registers 232 and 234, respectively.

Each of the 119 programmable memory bits can separately be written to with any combination of data, including synchronization (sync) pattern information, general data, error checking codes, and temperature and pressure calibration data. The EEPROM is 'block writeable', meaning that in the 'write' mode, the entire 120 bits of EEPROM are

25   programmed to a logical (binary) value of "1". Individual bits can be 'erased' (set to a logical value of "0" simply by clocking the chip to the bit's physical address and placing the chip into the 'erase' mode). The address location is preserved.

In this example, the first twelve data locations (000..011 in ROW 1) are reserved for sync. The next seventy one data locations (012..082 in ROWs 2 through 7) are for general

30   information and a value for a data validation algorithm such as CRC (Cyclic Redundancy Check). The next data location (083) contains the logic level (state) of the MTMS switch

220. A logical value of "1" indicates that the MTMS switch is open and a logical value of "0" indicates that the MTMS switch is closed.

As mentioned hereinabove, each transponder unit is suitably calibrated prior to its installation in a tire. The next twelve data locations (084..095 in ROW 8) hold temperature

5   calibration (e.g., defining point) data ("TEMP COMP"). The next twelve data locations (096..107 in ROW 9) hold pressure calibration (e.g., defining point) data ("PRESS COMP"). The next twelve data locations (108..113 and 114..119 in ROW 10) hold calibration (e.g., slope) information for temperature and pressure, respectively.

As counts N_T and N_P for temperature and pressure are generated, as described

10   hereinabove, they are stored in ROWs 11 and 12 of the overall memory space, which correspond to the temperature and pressure registers 232 and 234, respectively. Various predetermined values can be stored to indicate error conditions such as overflow and short-circuit.

OPERATING FREQUENCIES AND MODULATION

15   The transponder of the present invention is not limited to any particular operating frequency. The choice of operating frequency will depend largely upon factors such as where the transponder is mounted in relationship to the object it is monitoring, the location of the reader/interrogator antenna (108), and relevant government regulations permitting (conversely, restricting) data transmissions of the type set forth herein in selected portions of

20   the overall RF frequency spectrum.

An example of suitable operating frequencies for operating the transponder in the United States is 60 KHz to 490 KHz.

The transponder can be polled (and powered) by the reader/interrogator 106 at a first "interrogation" frequency (Fi), and the data stream can be transmitted back to the

25   reader/interrogator at a second "data carrier" frequency (Fc) which is, conveniently, a whole number multiple or fraction of the interrogating frequency. For example, Fc = Fi/2. Or, Fc = Fi/4. The frequency (Fc) at which the data stream is transmitted back to the reader/interrogator is independent of the data rate, which is established by the clock generator 224 and the baud rate generator 248. However, one having ordinary skill in the

30   art to which the present invention most nearly pertains will recognize that the range of available baud rates will typically be significantly less than the interrogation frequency (Fi).

The baud rate is preferably derived from the interrogation frequency (Fi) of the reader/interrogator, such as a whole number fraction thereof. For example, the baud rate may be set at Fi/32 (or, in the case of Fc=Fi/2, the baud rate can be set to Fc/16).

For example, the interrogation frequency (Fi) may be 125 KHz, and the data carrier (Fc) may be set to 62.5 KHz, or half of the interrogation frequency.

In another example, an interrogation frequency (Fi) of 13.56 MHz has been found to be suitable.

The data stream, such as the exemplary data stream described with respect to Figure 3C is impressed by the modulator circuit 246 onto the antenna 212, and transmitted to the reader/interrogator 106. It is within the scope of this invention that any suitable modulation scheme be employed, including amplitude modulation (AM), frequency modulation (FM), frequency shift keying (FSK), and phase shift keying (PSK). However, phase shift keyed (PSK) is preferred. AM modulation is not particularly well-suited to digital transmission. Frequency modulation schemes such as FM or FSK may be somewhat problematic with regard to propagating the data-modulated transponder output signal through the medium of a pneumatic tire (e.g., 104).

RATIO VERSUS SIGNAL STRENGTH

An added advantage of using the ratio N_T/N_P for a pressure indicator accrues because it has been determined that the ratioed value is less sensitive to variations in coupling between the reader/interrogator and the transponder than either of the N_T and N_P measurements taken alone. This is illustrated in Figure 3D which shows a graph 390 of measurement counts (on vertical axis 394) versus power (on horizontal axis 392). For a passive transponder 200 such as described in the preferred embodiment of this invention, the transponder power is supplied by the RF signal from the reader/interrogator (e.g., 106). If the RF coupling strength weakens due to transmission or reception problems including excessive distance or interference, then the power in the transponder 200 circuitry may decrease. It has been determined that for power levels below a certain value PWR_1, the relaxation oscillator 312 outputs a lower than normal frequency signal Fosc' and thus reduces the temperature and pressure counts N_T and N_P below what they should be for a given temperature or pressure. The effect is illustrated by the downward curve on the plot 396 of temperature count N_T and on the plot 398 of pressure count N_P as the plots extend

below the minimum power PWR_1. Fortuitously, the low-power effect is proportionally the same for both counts, so that the ratio N_T/N_P (plot 399) becomes relatively steady for all power levels down to a minimum power PWR_0 needed to operate the transponder 200. Thus, by determining (during calibration) and storing calibration data for the ratioed value of N_T/N_P in the transponder, the ability to determine a pressure-only reading which is relatively insensitive to coupling variations between the reader/interrogator and the transponder is both simplified and made more reliable.

IMPROVEMENTS, GENERALLY

The present invention deals with a new "RFIQ™" transponder 400 (see Figure 4A) which implements improvements to the previous model, "3070C" transponder 200 described hereinabove. A number of improvements have been made, and new features incorporated, including, but not limited to:

- Lower power consumption.
- Increased oscillator stability vs. Power or Frequency.
- Increased resolution of temperature and pressure counts.
- Increased electrostatic discharge (ESD) protection to more than 2200V.
- Increased, programmable modulation index (magnitude of PSK modulation applied to the RF signal).
- Reduced number of external connection pins for programming and testing.
- Increased Digital and Analog Testability.
- Increased to 192 bits of data stream.
- Increased to 156 bits of programmable EEPROM.
- Programmable with the antenna (coil) attached.
- 6 bits of parity – 1 bit for each 4 bits of NT, NP data.
- Programmably scale currents to independently optimize reading counts for pressure and temperature.
- 3V Battery powered mode for use in "active" implementations of the transponder ("active tags").
- Power-On Reset.
- Base-band data output on a test pin.

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PROBLEMS TO BE SOLVED

In particular, there are general problems with the previous transponder design 200 described hereinabove. It is believed that improvements which are the subject of the present invention provide solutions for a number of these problems:

5
- The relaxation oscillator of the previous design transponder 200 could be adjusted to optimize the pressure and temperature counts (NP and NT) for a desired pressure and temperature range, but the adjustment could only be accomplished during integrated circuit production. It is desirable to provide a way to optimize the counts NP and NT after integrated circuit production.

10
- When the previous design transponder 200 is used (as a passive transponder), inaccurate results may be transmitted when the transponder operates at too low a power input, such as during startup, or when distant from the reader/interrogator. (For example, refer to Figure 3D.) In addition, the previous model would start modulating ("transmitting") as soon as it received an interrogation signal of any strength, and would

15
start the transmission at a random location in the data word. If the initial signal was weak (from a distant reader/interrogator), then the voltage supplies could be insufficient to produce valid temperature and pressure readings. And if modulation started before sufficient power levels were developed, then the power drain of signal modulation would aggravate the insufficient power problems. A further problem occurs if the relaxation

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oscillator does not start each measurement cycle in a consistent, defined state.

- The previous design transponder 200 has a fixed modulation index (magnitude of RF signal modulation) which is determined during integrated circuit production. It is desirable to provide a way to optimize the transponder for different combinations of antenna ("coil") 210 and reader/interrogator 106, and for different operating conditions.

25
Also, certain transponder applications utilize an external zener clamp across the antenna 210 for better stability, but the zener can cause the previous design transponder 200 to be "read-limited".

- Although the previous design transponder 200 can have certain operating characteristics adjusted ("trimmed") during manufacture (e.g., current scaling via size

30
adjustments to transistors), these manufacturing changes are permanent, and not easy to vary from transponder to transponder. Furthermore, if trim settings were to be

implemented in programmable memory (e.g., EEPROM), then there would be other problems with accessing those settings during power-up, and continuously rather than through row (242) and column (240) decoders.

Other improvements and problem solutions may become evident in the description to follow.

GENERAL DESCRIPTION

The improved RFIQ™ transponder 400 (compare 200, 102) is a custom CMOS, low voltage Integrated Circuit ("IC", or "chip") that can measure temperature and pressure as a low-frequency "passive" (RF signal-powered) transponder or as an "active" (battery-powered) measurement system. The IC provides programmable trimming that determines: (a) if the part is active or passive, (b) to adjust temperature and pressure resolution, and (c) modulation index and coil clamping strength (when in the passive mode).

In the passive mode, the IC develops power from a reader/interrogator RF signal that is coupled to an external LC circuit across the transponder antenna inputs. The transponder uses the signal received to provide power and to generate an on-chip clock. The transponder sends back its memory contents to the reader by modulating the impedance of the antenna, which is known as "back scattered modulation". The reader demodulates the returned data to get the sensor identification ("ID") as well as sensor data and calibration constants needed to interpret the data.

The transponder sends a 196-bit serial phase-shift-keyed (PSK) data-stream as sixteen, 12-bit words. The first 12 bits are the programmable sync word, with each sync bit being 1.5 bits wide. Next, 144 bits of EEPROM are transmitted that are of normal bit width. The 144 bits contain the unique ID code of the transponder, the calibration constants for temperature and pressure data, and a CRC for error checking. The transponder then sends 36 bits of data: a 12-bit temperature count (NT), a 12-bit pressure count (NP), and a 12-bit word consisting of five unused bits as 1's, 1 bit for the state of the MTMS over-temperature sensor, and 6 bits of even-parity, with one bit of parity for every four bits of NP and NT data.

In the active mode, the transponder must be controlled by external hardware. The controlling hardware provides power to the IC and a clock signal via either the CLK or VB pads. The IC shifts out its data on the DATA pad on every falling edge of the clock. The

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clocks must be given at a precise clock rate so that temperature and pressure are collected during fixed periods of time and therefore, the hardware can optimize the clocking time per bit to get the highest resolution for temperature and pressure. The IC can operate down to as low as 2.8V in active mode.

5   As either a passive or active tag (transponder), the IC can be tested after assembly by applying power and talking to the chip via a 4-pin interface. This interface allows the user access to the chip's EEPROM and allows testing the chip functions. The EEPROM data can be read, cleared, or programmed and the oscillator tested by directly reading the frequency. The chip sensor oscillator can also be tested and provides a second method for reading

10   temperature and pressure in the active mode.

OVERVIEW OF THE RFIQ™ TRANSPONDER CIRCUITRY

Figure 4A is comparable to Figure 2, and is a block diagram of a relevant portion of an improved RFIQ™ transponder 400 (compare 102, 200), illustrating the following signals, terminals and functional blocks (sections), and their interconnections with one another. This

15   exemplary system is described as an embodiment which preferably measures pressure and temperature, but it is within the scope of the invention to include measurement of other parameters which employ suitable sensors.

The transponder 400 is preferably implemented on a single integrated circuit (IC) chip shown within the dashed line 402 (compare 202), to which are connected a number of

20   external components. Other dashed lines in the figure indicate major functional "blocks" ("sections") of the transponder 400, and include a block 438 (compare 238) of addressable memory, and a sensor interface section 406 (compare 206).

The components external to the IC chip 402 include an antenna system 410 (compare 210) comprising an antenna (coil) 412 and an optional capacitor 414 connected across the

25   coil 412 to form an L-C resonant tank circuit, an external precision resistor (Rext) 416 (compare 216), an external pressure-sensing capacitor (C_p) 418 (compare 218), and an optional external maximum temperature measurement switch (MTMS) 420 (compare 220). Each external component has an appropriately labeled connection pad as shown in Figure 4A: VA and VB for the antenna system 410; Rext, Cp and MTMS for the high side of the

30   precision resistor 416, the pressure-sensing capacitor 418, and the maximum temperature measurement switch 420, respectively. The ground connection for the analog external

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components Rext, Cp, and MTMS should be made via the analog ground AGND pad. The other ground pad (GND) is for the ground connection of external digital connections. The remaining connection pads are for use in active or test modes of transponder 400 operation as described hereinbelow.

5   The antenna 412 may be in the form of a coil antenna, a loop antenna, a dipole antenna, and the like. It is mainly used when the transponder 400 is in the passive mode. Alternatively, when the transponder 400 is in the active mode, the antenna system 410 may not be present, and the signal output by the transponder 400 may be provided via direct connection to a DATA pad. In the main hereinafter, a transponder having a coil antenna, 10 and used in the passive mode is described.

The transponder IC 402 includes interface circuitry 422 (compare 222) for processing an RF signal, such as an un-modulated carrier signal of frequency Fi (e.g., 125 kHz) received by the antenna 412, and for rectifying the received RF signal so that it can be used to power the transponder 400 operating in passive mode. The signal processing 15 includes passing on a suitable form of the incoming signal to be used for generating timing/clock pulses for the transponder 400, and also includes applying modulation to the carrier signal for transmission by the antenna system 410.

The rectified carrier signal is clamped to a maximum of approximately 13.0 volts to prevent breakdown of the IC 402 substrate. The clamped, rectified signal has a voltage Vpp 20 which can be read at a VPP pad, and ranges from 0 – 13 volts. The Vpp voltage is then shunt-regulated to a maximum of 6.5 volts, and designated as supply voltage (or "input voltage") Vxx which can be read at a VXX pad. The Vxx voltage level follows the Vpp voltage, and is about 6.2 volts for a typical received RF signal. Voltage Vxx is regulated to prevent voltages high enough to potentially damage CMOS circuitry in the IC 402.

25   The voltage Vxx is provided to a power-on reset (POR) circuit 482 (which is new to this model transponder), and also to a regulation and bandgap reference circuit 423 (compare 222) for providing various voltage supplies to the circuitry on the IC chip 402.

The power-on reset circuit 482 is provided to ensure that the transponder 400 will not begin to record sensor readings or to transmit data until enough power is being supplied 30 by the received carrier signal to allow proper functioning of the transponder 400. The POR circuit 482 evaluates the voltage Vxx level and outputs a reset signal which is not released

until the Vxx voltage is deemed sufficient. If desired, such as for test purposes, the reset signal can be imposed from outside the chip 402 through an RES connection pad.

In the passive mode, as long as the supply voltage Vxx is sufficient (at least 4 volts as determined by the POR circuit 482), the regulation and bandgap reference circuitry 423 will regulate voltage Vxx to provide a regulated analog supply voltage Vcc of approximately 3 volts, with an operating range of 2.8 V (minimum voltage for a stable oscillator 452) to approximately 3.5 V.. The digital supply voltage Vdd is regulated by a source follower connected to voltage Vcc and can supply current independently of voltage Vcc (compare with previous method as in Figure 3B, described hereinabove). Voltage Vdd is typically about one threshold below Vcc, or approximately 2.5 volts, ranging from 1.2 V (minimum voltage for stable logic and memory operation) to approximately 3.5 V, and supplies both the digital logic and the EEPROM (memory) array 436 during reading. During transponder programming, voltages Vcc and Vdd are not affected by applying power to pad VPP. The voltages Vcc and Vdd can be read externally via their correspondingly-named connection pads (VCC and VDD). Also, in active (battery-powered) mode, the regulators can be overridden by applying external power to the VCC and VDD pads. Finally, for circuits which need a stable reference voltage, the regulation and bandgap reference circuit 423 provides a temperature-independent bandgap voltage Vbg. The reference voltage Vbg is also independent of the chip supply voltage Vxx as long as the voltage Vxx is above a minimum operating level. The regulation and bandgap reference circuit 423 will output a substantially temperature-independent voltage Vbg of approximately 1.20 volts over a transponder operating temperature range of, for example, –40 to 150 degrees C. The bandgap voltage Vbg is used as a reference voltage by the Vxx, Vcc and Vdd regulators 423 as well as the relaxation oscillator 452 and the power-on reset circuit 482.

The interface and rectification circuitry 422 also provides the received RF signal, preferably at the input frequency (Fi) it is received, to a timing and clock generator circuit 424 (compare 224, 226) which generates clock signals in a known manner for controlling the timing of other circuits on the IC chip 402. The generated clock signal is a 50% duty cycle square wave, preferably at frequency Fi, and is independent of any modulation applied to the antenna system 410 by the transponder 400 for the transponder's PSK transmission. The timing and clock generator circuit 424 also divides down the system clock to develop

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timing for addressing of the data in the addressable memory 438, and for the modulation.

For example, the system clock frequency Fi is divided by two to determine the frequency of

the PSK modulated return carrier signal. Other divisions of the frequency Fi are used for

determining the baud rate for data transmission. In active or test modes of operation, the

5   timing and clock generator circuitry can be bypassed or used as a buffer for direct input of

the clock signal via a CLK pad or the VB antenna pad.

From the timing and clock generator 424 the various clock signals are passed to

several control logic circuits: the column decoder 440 (compare 240), the column to data

converter 441, and the row decoder & N_T, N_P control 442 (compare 242) which control

10   access to data stored in the addressable memory 438. The clock signals are also used by the

row decoder & N_T, N_P control 442 to control the timing of the relaxation oscillator 452 and

the data capture circuitry 454, which generate and store the temperature N_T and pressure N_P

readings (counts) in the temperature register 432 and pressure register 434. Thus the row

decoder & N_T, N_P control 442 functions as a "timing generator" secondary to the timing and

15   clock generator 424.

The addressable memory block 438 includes an EEPROM array 436 (compare 236)

and several hardware registers 432, 434, and 435 (compare 232 and 234). The EEPROM

436 is programmed with a variety of stored information which will be described in detail

hereinbelow.

20   The last two rows of the EEPROM (e.g., rows 14 and 15) constitute a trimming bits

section 436b which is programmed to store trimming information. The trimming

information: (a) controls the scaling of the current (in the base-emitter voltage to current

converter 450) supplied to the relaxation oscillator 452 to optimize the pressure and

temperature count resolution, (b) sets the modulation index in the modulation circuit 446 to

25   optimize signal transmission for a given antenna system 410 and for a given transponder

application, (c) sets the mode of operation (active or passive), and (d) optimizes the

impedance of a clamp on the voltage Vpp across the rectification circuit 422. Utilizing the

trimming lines 485, the trimming information stored in the trimming bits 436b can be

directly read by the circuits it affects (e.g., 450, 446, 484, 422, 482) at any time during

30   transponder operation (active or passive). Alternatively, as in certain test and programming

modes, the trimming bits 436b can be accessed for external reading and writing

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(programming) along with the rest of the EEPROM 436 memory via the DATA connection pad, as controlled by the test logic circuitry 484, and communicated by a transponder data line 444 through the column to data converter 441.

As described hereinabove with reference to the previous model transponder 200, the temperature and pressure registers (432 and 434 respectively) are each a hardware register holding the count (e.g., 12 bit) of a down-counter which is clocked by the sensor data signal of frequency Fosc' coming from the sensor interface section 406.

The parity, MTMS 435 section of memory is also new to this model of transponder 400. It is implemented as a register in hardware with, for example, 12 bits of stored data. Five bits are permanently set (value = 1), then there is a bit which sets/clears according to the open/closed (1/0) status of the MTMS switch (closes if exposed to excessive temperature), and finally six bits registering the parity of the pressure and temperature counts: three parity bits for the pressure register 434 count N_P, and then three parity bits for the temperature register 432 count N_T. The parity bits are continuously updated during sensor data capture, following the changing counts in the N_P and N_T down-counters (the pressure 434 and temperature 432 registers, respectively). Each parity bit represents the parity of 4 sequential bits (a "nibble") in the corresponding pressure 434 or temperature 432 register; with the most significant parity bit representing the most significant nibble of the count, the middle parity bit for the middle nibble of the count, and the least significant parity bit for the least significant nibble of the count.

The sensor interface portion 406 (compare 206) of the transponder chip 402 consists of the base-emitter voltage to current converter 450 (compare 250) with connection pad "Rext"; the relaxation oscillator 452 (compare 252) with connection pad "Cp"; the data capture circuitry 454 (compare 254); and the "MTMS" connection pad and line 459 connecting it to the MTMS bit in the parity, MTMS register 435 (compare 236 for the previous location of the MTMS bit).

The base-emitter voltage to current converter 450 functions in a similar way to the converter 250 which is described in greater detail hereinabove with reference to sections 306 to 310 of Figure 3. For improved performance, the circuitry of sections 306, 308 and 310 in the new base-emitter voltage to current converter 450 utilizes cascodes instead of single stage current mirrors (e.g., for transistors P1, P2, P4, P6), and the external resistor Rext

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416 may have a different preferred resistance value, such as 500 kilohms. Cascodes are desirable because of their increased power supply rejection ration (PSRR). Also, in a feature to be described more fully hereinbelow with reference to Figure 5, the final stage

5   510 (compare 310) of the base-emitter voltage to current converter 450 is connected in a different way to section 308, and works in conjunction with programmed settings in the trimming bits register 436b to provide a scaled proportional-to-temperature current I(T)B on the line 451, 511 (compare current I(T)/N on line 251, 311) to the relaxation oscillator circuitry 452 (compare 252). In contrast with the previous design, the current scaling circuit 510 (compare 310) can scale the current I(T) by a variable scaling factor "B", as determined

10   by programmed settings in the trimming bits register 436b.

The relaxation oscillator 452, under the timing control of the row decoder & N_T, N_P control circuit 442, works in conjunction with the external capacitive pressure sensor Cp 418 to generate a signal on line 453 (compare 253) with frequency Fosc' which is indicative of either the ambient temperature or the ambient pressure, depending on the timing window

15   determined by the row decoder & N_T, N_P control circuit 442. The data capture circuitry 454, under the timing control of the row decoder & N_T, N_P control circuit 442, directs the Fosc' signal to the appropriate hardware register (depending on the timing window): to the temperature register 432 via line 455, or to the pressure register 434 via line 457.

The current scaling circuit 510 (part of the base-emitter voltage to current converter

20   450) and the relaxation oscillator 452 have improvements compared to the relaxation oscillator 252, and the MTMS 420 status is directed to a different memory location (register 435) than in the previous implementation (EEPROM 236). Otherwise, the sensor interface section 406 functions essentially the same as the corresponding section 206 in the previous model 3070C transponder 200.

25   As described hereinabove with reference to the previous model transponder 200, the term "ambient" refers to the parameter being measured in the vicinity of the transponder 400, or more particularly in the vicinity of the respective sensors associated with the transponder 400. Also, references made herein to "pressure readings", "pressure counts", "pressure response", "pressure register" and the like generally refer to "pressure" as

30   measured by this transponder technique which actually produces a hybrid pressure-temperature reading. When this hybrid reading has been processed to remove its

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temperature component, the reading is referred to as a "pressure-only" reading.

In conjunction with the column decoder 440 and the row decoder 442, the column to data converter 441 controls the sequence in which signals (i.e., data) are output on a line 444 (compare 244) to a modulation circuit 446 (compare 246) which, via the interface and rectification circuitry 422 (compare 222), communicates selected measured tire operating characteristics in a data stream via the antenna system 410 to an external reader/interrogator (e.g., 106). The line 444 also communicates the data stream to the test logic circuit 484 where it can be directly accessed via the DATA connection pad.

The modulation circuit 446 converts the data stream from line 444 to a representative sequence of impedance changes (modulations) which are applied to the antenna system 410 through the interface and rectification circuit 422. A new feature of the transponder 400 of the present invention is the ability to modify the modulation index (magnitude of modulation) to suit operating power levels and to select (via the trimming bits 436b) a modulation index optimized for the individual transponder 400, antenna system 410, and reader/interrogator 106 in use.

In passive mode operation, an RF carrier signal from an external source (e.g., a reader/interrogator 106) is received by the antenna 412. This RF signal is rectified and used to power the RF transponder 400 as well as providing the timing/clock signals. Modulating information applied by the modulation circuit 446 is used to alter characteristics (e.g., impedance, resonant frequency, etc.) of the LC tank circuit of the antenna system 410. These alterations are sensed as changes in load by the external reader/interrogator 106 and are decoded, providing communication of data back from the RF transponder 400 to the external reader/interrogator 106. Because the transponder 400 passive power is derived from the received RF signal, and because modulation of that signal drains off some of that power, the POR circuit 482 maintains a reset signal during passive power-up, and will not clear the reset signal (thereby allowing modulation), until the transponder power levels are high enough to assure stable operation of the transponder 400 during modulation.

The test logic circuit 484 enables tests that can be performed at all phases of transponder production and use, including wafer sort, initial board assembly level programming, programming at the pre-calibration stage, calibration and trimming of the transponder, and post-calibration programming to adjust the trimming bits 436b for

encapsulation-induced offset error.

More detailed explanations of significant portions of the RFIQ™ transponder 400 of this invention are presented in the following sections.

MEMORY ASSIGNMENTS AND THE DATA STREAM

5   The addressable memory block 438 is organized in a way which provides a data stream that is improved over that of the previous model 3070C transponder 200. The column decoder 440, the column to data converter 441, and the row decoder & N_T, N_P control circuit 442 work together to control the flow of data in and out of the addressable memory block 438. When operating in the active or passive modes (i.e., not in a test or programming mode), the circuits 440, 441 and 442 access the memory locations one at a time in sequence from the first address to the last (most significant bit to the least significant bit in each data "word", with words sequenced from the lowest numbered word to the highest), thereby producing a serial string of data for transmission. It will be seen from the following description that the rows to be included in the data stream are selected according to the mode of operation (i.e., passive/active, or a variety of test and programming modes). An added function of the row decoder & N_T, N_P control circuit 442 is to control the sensor interface circuitry 406 (via line 487) so that it is accumulating temperature-related counts in the temperature register 432 during one portion of the data transmission (e.g., while transmitting words/rows 2 through 6), and pressure-related counts in the pressure register 434 during another portion of the data transmission (e.g., while transmitting words/rows 9 through 13), both accumulations to be completed in time for the counts to be read back out of the registers 432 and 434 when their part of the data stream is due (e.g., words 14 and 15).

Figure 4B (compare Figure 3C) is a "map" of the addressable memory block 438, showing its physical organization (by "rows") and also showing the organization of the active or passive mode data stream (by "words"). In the preferred embodiment of transponder 400 described herein, each word or row is 12 bits (or columns) in length, and there are 16 words in the data stream, comprising a total of 192 bits (12 times 16). The drawing of the memory block 438 in Figure 4A is helpful in understanding the physical organization. It should be noted that the rows 1 to 13 of physical memory (EEPROM 436) correspond to the words 1 to 13 of the data stream, but the rows 14 and 15 of physical

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memory (EEPROM 436) are not part of the data stream. Instead, the temperature register 432 is read out as word 14, and the pressure register 434 is read out as word 15 of the data stream. The final word of the data stream, word 16, is read out of a hardware register of physical memory (the parity, MTMS register 435).

5   The EEPROM 436 portion of the exemplary addressable memory block 438 comprises 180 cells arranged in a 12 column by 15 row array. Each cell is made up of at least one n-channel select gate and one corresponding EEPROM transistor. The first 13 rows (sync, I.D., calibration, CRC 436a) are readable in the normal read modes whether the transponder 400 is programmed to be active or passive. The EEPROM memory locations in

10   these first 13 rows are selected in the usual way, with one n-channel transistor row selection gate per EEPROM transistor. The EEPROM cells at rows 14 and 15 (trimming bits 436b) hold the data for 12 bits of trimming information, and are configured differently to facilitate their special role in the transponder. Each trimming bits 436b EEPROM cell has two gates instead of one, adding a special READ_TRIM selection gate in series with the row selection

15   gate so that the trimming bits 436b cannot be added to the data stream unless the READ_TRIM selection gate has been enabled as in certain test modes of transponder operation. Another feature of the special trimming bits 436b register is that each trimming bits 436b cell also has an added sensing line to communicate the EEPROM bit setting (programmed trimming information) to appropriate sections of the transponder 400 circuitry

20   as needed.

        Thus the EEPROM 436 and associated logic are structured so that: The trimming bits 436b data can be read externally by a "READ_TRIM" test mode which reads out the bits sequentially as words 14 and 15 in the data stream in place of the temperature and pressure counts. In a "READ" test mode, as in normal operation, the trim bits are not seen

25   in the data stream, but are still accessed by sense amplifiers to communicate programmed trim settings to appropriate sections of the transponder 400. In a "WRITE" test mode, all the EEPROM 436 cells (including the trim bits 436b) are addressed simultaneously and are written to. This in effect writes '1's to all the EEPROM cells, giving them high thresholds. In an "ERASE" test mode, individual cells can be erased (programmed to '0', given a low,

30   negative, threshold): as the clock CLK signal indexes through the EEPROM cell array, a cell at the intersection of the column addressed and the row addressed is erased by raising

the voltage on the VPP pad to the programming voltage and enabling the erasure by raising the DATA pad high.

Referring to figure 4B, the map illustrates an exemplary organization wherein the first twelve data locations (bits 000..011 in row 1) are reserved for synchronization ("sync") data. The next forty-eight data locations (bits 012..059 in rows 2 through 5) are for general information identifying the individual transponder 400. As mentioned hereinabove, each transponder unit is suitably calibrated prior to its installation in a tire. The next twenty-four data locations (bits 060..083 in rows 6 through 7) hold temperature calibration data (e.g., a defining point and a slope). The next twenty-four data locations (bits 084..107 in rows 8 through 9) hold pressure calibration data (e.g., a defining point and a slope). The next thirty-six data locations (bits 108..143 in rows 10 through 12) hold additional identifying information concerning the IC chip 402. The next twelve data locations (in row 13) hold four bits of identifying information about the chip calibration (bits 144..147), and an eight bit value (bits 148..155) for a data validation algorithm such as CRC (Cyclic Redundancy Check). The next two words in the data stream (words 14..15, bits 156..179) are read from the temperature register 432 and the pressure register 434, respectively. The final word of the data stream (word 16, bits 180..191) is read from the parity, MTMS register 435, which contains five "open" bits (bits 180..184), then one bit (bit 185) containing the logic level (state) of the MTMS switch 420, and finally six bits (bits 186..191) containing 3 bits each for the parity of the pressure count followed by the parity of the temperature count. The five open bits are unused, and are fixed as logical "1" values.

The column decoder 440, column to data converter 441, and row decoder & N_T, N_P control 442 circuits coordinate addressing and access to the addressable memory block 438.

The column decoder 440 consists of a four-bit synchronous counter that addresses a 1-of-12 decoder. The outputs from the column decoder 440 address the 12 columns of the memory array during programming and reading. To address a column, the address n-channel device routes a low power current-source to charge the addressed column. If a bit is written to, the column will be pulled high, but if erased, the column will be pulled low. The output of the current-source is buffered and drives a transponder data line 444 that goes through the column to data converter 441 to the modulation 446 and test logic 484 circuits. The columns are sequentially addressed from column 1 to column 12 at the rate of a timing

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logic clock signal provided either by the timing and clock generator 424, or externally via
the CLK pad. After addressing column 12, the column decoder 440 triggers the row
decoder & N_T, N_P control 442 to clock it to the next row and also cycles itself back to
column 1. Whenever a reset signal (turned on, then off) is received from the power-on reset

5   circuit 482 (or via the RES pad), the column decoder 440 and the row decoder & N_T, N_P
control 442 will reset their addressing sequence to start at column 1 of row 1, i.e., the first
bit or cell in the addressable memory block 438. The column decoder 440 serially addresses
the EEPROM 436 array in any of the reading modes of operation or during erasing. In the
WRITE test mode it has no effect, since the entire EEPROM memory is simultaneously

10   addressed for the WRITE operation.

The row decoder & N_T, N_P control 442 is a 4-bit synchronous counter that addresses
a 1-of-16 decoder. The decoder addresses 13 rows of EEPROM data memory 436a from
rows 1 though 13. In the WRITE, ERASE, and READ_TRIM test modes, it also addresses
rows 14 and 15 of the EEPROM memory 436b for the trimming bits. During normal

15   reading (active or passive mode), the decoder addresses the temperature 432 and pressure
434 hardware registers at row addresses 14 and 15, respectively. Regardless of operating
mode, the row-16 address is directed to a special data row: the parity, MTMS 435 hardware
register. In the READ and ERASE test modes each row is addressed sequentially on the
falling edge of the last bit of the column decoder 440. In the passive or active mode, a reset

20   signal sets the row decoder & N_T, N_P control 442 to row 1, which is the sync word. In the
WRITE mode, all the rows are simultaneously addressed, which pulls all select lines and
control gates to voltage Vpp. As mentioned hereinabove, an added function of the row
decoder & N_T, N_P control circuit 442 is to control the sensor interface circuitry 406 so that it
is accumulating temperature-related counts in the temperature register 432 and pressure-

25   related counts in the pressure register 434 during their designated time periods (data
collection windows).

VARIABLE MODULATION INDEX

As described hereinabove, in passive mode operation, when a reset signal from the
power-on reset circuit 482 has been released, the modulation circuit 446 converts the data

30   stream from line 444 to a representative sequence of impedance changes (modulations)
which are applied to the antenna system 410 through the interface and rectification circuit

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422. A feature of the transponder 400 of the present invention is the ability to dynamically modify the modulation index (magnitude of modulation) in response to operating power levels, and to programmably select (via the trimming bits 436b) a modulation index optimized for the individual transponder 400, antenna system 410, and reader/interrogator

5   106 in use.

In passive mode operation, an RF carrier signal from an external source (e.g., a reader/interrogator 106) is received by the antenna 412. This RF signal is rectified and used to power the RF transponder 400 as well as providing the basis for the timing/clock signals. The modulation circuit 446 imposes the data stream onto the incoming RF carrier signal by

10 altering the impedance load on the LC tank circuit 412/414 of the antenna system 410. During transmission by the external reader/interrogator 106 to a transponder 400 which is within a suitable range, the reader/interrogator antenna 110 is coupled to the transponder antenna system 410. Because of this coupling, the alterations in load imposed on the transponder antenna system 410 are sensed by the external reader/interrogator 106 as

15 changes in its own antenna 110 loading and are decoded, providing communication (i.e., "transmission") of data back from the RF transponder 400 to the external reader/interrogator 106. This is known as "back-scattered modulation." The modulation pattern preferably used is a phase-shift keyed (PSK) technique, wherein the modulation causes a periodic variation in the amplitude of the carrier signal and a change in the phase of that periodic

20 variation signifies a bit-value change in the data stream. The sync word at the beginning of the data stream employs known methods to correlate the modulation phase with logical state of the bits to follow. In order to accomplish the amplitude modulation, the low frequency square-wave data stream is combined with a higher frequency (e.g., 16 times higher) waveform to create a PSK_MOD waveform which has a 180 degree phase shift in the

25 PSK_MOD square-wave for every change of logic state in the data stream.

The amplitude variation in the modulated signal is implemented by modulating (switching in and out) a modulation load between the antenna system 410 inputs at pads VA/VB and ground. A feature of this invention is that the modulation load (modulated load) can be programmably varied in a binary fashion via the settings programmed into the

30 bits 0..3 of the trimming bits register 436b. For example, ignoring the non-loaded (infinite impedance) case, the trim bit settings can vary the impedance of the modulated load from a

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highest impedance (minimum load) of approximately 10K down to a lowest impedance (maximum load) of approximately 667 ohms (one fifteenth of the maximum impedance). Another feature of this invention is that the modulated load applied to the antenna system 410 is dynamically varied during operation by the voltage Vxx such that at a low voltage Vxx (such as results from being distant from the reader/interrogator 106) the modulated load seen by the antenna system 410 is low (high impedance), but increases as the transponder 400 is brought into the near field of the reader/interrogator 106. Since a transponder 400 in passive mode derives its operating power from the RF power seen at the antenna system 410, this feature prevents the modulation from draining off too much of the energy needed to power the transponder when it is at far distances from the reader/interrogator 106. Also, in some situations a Zener diode may be desired as an external clamping device across the antenna system 410, 710 in order to dissipate excessive power when high power reader/interrogators are used. If so, then the dynamically-varied modulation feature helps compensate for the read-limiting effect of the Zener diode.

The magnitude of amplitude modulation imposed by the transponder modulation circuit 446 can be expressed as a "Modulation Index," or "Percent Modulation," which is calculated as follows:

$$\text{Modulation Index} = 100 * (VP_2 - VP_1) / (VP_2 + VP_1)$$

where VP_2 is the peak voltage of the un-modulated waveform, and VP_1 is the peak voltage of the loaded-down peaks in the modulated waveform. The resultant Modulation Index can be seen as a percentage representative of the amount of reduction in the RF signal energy imposed by the increased load during modulation.

Figure 5 illustrates a modulator 700 in a detailed schematic representation of the modulation circuit 446 (compare 246), which implements the variable modulation index of this invention. A capacitor 714 (compare 414, 214) is connected across an antenna coil 712 (compare 412, 212) to form an L-C resonant tank circuit which is the antenna system 710 (compare 410, 210). The antenna system 710 is connected to the transponder chip 402 via connection pads VA and VB, which are accessed both by the interface & rectification module 422 and the on-chip portion 446 of the modulator circuitry 700.

The antenna system 710 is driven by a modulation load comprising one or more of the output stage transistors M1..M4 and one or more of the output stage transistors

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M5..M8. The output stage transistors M1..M8 are "low-doped drain" transistors in order to best handle the potentially high voltages generated on the antenna system. Since the interface & rectification module 422 is performing a full-wave rectification of the signal received on the antenna system 710, the two terminals VA and VB of the antenna system 710 are separately modulated to achieve symmetric modulation effects. The output stage transistors M1..M8 have a range of physical sizes, expressed as a "width" by a "length" (W x L). For example: transistors M1 and M5 are 80μm x 8μm ("μm" units are micro-meters, or microns); M2 and M6 are 40μm x 8μm; M3 and M7 are 20μm x 8μm; M4 and M8 are 10μm x 8μm. As an alternative to manufacturing differently sized transistors, each of the transistors M1..M8 could be made up of one or more transistors in parallel, with physical areas which add up to the desired total physical area (e.g., transistor M1 could comprise eight 10μm x 8μm transistors in parallel). The output stage transistor M1..M8 physical sizes are chosen to yield loads in binary steps from one output stage transistor to the next, within each set of transistors M1..M4/M5..M8 for an antenna terminal VA/VB. It is known that the linear mode impedance of a transistor such as the output stage transistors M1..M8 used in this circuit 700 (e.g., FET transistors) can be represented as:

$$Z = L / (W * k * (V_{GS} - V_{Th})) \qquad \text{[EQ. C]}$$

where Z is the impedance, L and W are the "length" and "width" of the transistor, k is a simplifying "constant" including parameters which do not change between transistors in this example, V_{GS} is the gate-to-source voltage (e.g., gate to ground), and V_{Th} is the threshold voltage for the transistor (e.g., 0.5 V). Thus, in this example, transistors M4 and M8 each have an impedance proportional to one over their "width", or 1/10; transistors M3 and M7 each have an impedance proportional to 1/20; transistors M2 and M6 each have an impedance proportional to 1/40; and transistors M1 and M5 each have an impedance proportional to 1/80.

Connected to pairs of transistors M1/M5..M4/M8 are four level shifters LS1, LS2, LS3 and LS4, each of which is controlled by the control logic circuitry 747, and are supplied an additional power supply voltage Vxx. The control logic 747 and the circuitry preceding it are operated with logic level voltages, i.e., voltage Vdd. The level shifters LS1..LS4, when turned on by the control logic 747, output the higher voltage Vxx to the gates of the transistors connected to them. Thus the gate-to-source voltage V_{GS} in the

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equation EQ. C becomes the input voltage Vxx which is derived from the rectified input RF signal, and therefore is proportional to it up to the limit voltage imposed by the interface & rectification circuit 422. As can be seen in the equation EQ. C, the impedance of the output stage transistors M1..M8 is inversely proportional to the voltage $(Vxx - V_{Th})$. This is an exemplary technique employed to vary the modulation index according to variations in the incoming power level.

The control logic 747 has two main sets of control inputs: the trim bit information, and the phase-shift-keyed data stream $\overline{PSK\_MOD}$ (the PSK_MOD signal inverted as it passes through another control logic element: a NOR gate 796).

The PSK_MOD signal is formed by known techniques such as combining the data stream and a clock signal in an exclusive or (XOR) gate 794. In this embodiment, the clock signal is a square-wave signal "SYS_CLK/2" divided down to half the frequency of the system clock signal, which obtains its frequency from the RF carrier signal received by the antenna system 710, 410. The data stream operates off a column-decoder clock signal with a frequency of the system clock signal divided by 32. For example, with a 125 KHz RF signal from the reader/interrogator 106, the system clock frequency will be 125 KHz, the SYS_CLK/2 signal frequency will be 62.5 KHz, and the data stream will be clocked at a frequency of approximately 3.9 KHz, creating 16 cycles of the SYS_CLK/2 signal for each cycle (i.e., bit) of the data stream. The data stream is introduced to the modulation circuit 446, 700 via the line 444 from the column to data converter 441 as described hereinabove. It is a feature of the present invention to use a sync delay 792 circuit to impose a synchronization delay on the SYS_CLK/2 signal before it is applied to the XOR gate 794. The sync delay 792 provides enough delay (e.g., 400 nano-seconds) to synchronize the phase changes of the SYS_CLK/2 signal with the phase changes of the data stream signal. A delay to synchronize is needed due to the delays encountered by the data stream as it passes through the many gates in the transponder memory 438 and the column and row decoders 440, 442 and the column to data converter 441. Synchronization is desirable so that the only phase changes imposed by the XOR gate 794 on the PSK signal are those due to bit state changes in the data stream.

The PSK_MOD signal is passed through the NOR gate 796 which serves as an on-off switch controlled by either the RESET signal or a "TESTING" signal (indicating if the

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transponder 400 is in a test mode where modulation is not desired). If either the RESET signal or the TESTING signal is high, the PSK_MOD signal will be blocked by the NOR gate 796 and no modulation will occur.

An example of a possible stage 747a of the control logic 747 is illustrated in Figure

5   5A.. In this embodiment of the transponder 400, there are four bits (e.g., bits 0..3, or TRIM_BIT0, TRIM_BIT1, TRIM_BIT2, and TRIM_BIT3) in the trimming bits register 436b which control the modulation index, one bit for each level shifter LS1..LS4. As can be seen from the illustrated circuit 747a, the NAND gate 749a will use the setting of the trim bit TRIM_BIT0 (436b.0) to allow the $\overline{PSK\_MOD}$ signal to pass on to the level shifter

10   LS1 if TRIM_BIT0 is programmed high, or to prohibit the $\overline{PSK\_MOD}$ signal from affecting the level shifter LS1 if TRIM_BIT0 is programmed low. (When passed on, the $\overline{PSK\_MOD}$ signal will also be inverted by the NAND gate 749a, becoming the PSK_MOD signal.) It can be seen that, with a similar set of control stages, the trimming bits 0..3 will determine which of the output stage transistor pairs M1/M5..M4/M8 are used

15   to modulate the antenna system 710 according to the PSK_MOD signal, thereby programmably varying the modulation index.

Although the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only preferred embodiments have been shown and

20   described, and that all changes and modifications that come within the spirit of the invention are desired to be protected. Undoubtedly, many other "variations" on the "themes" set forth hereinabove will occur to one having ordinary skill in the art to which the present invention most nearly pertains, and such variations are intended to be within the scope of the invention, as disclosed herein.

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CLAIMS:

1.   An RF transponder (102, 200, 400) comprising an antenna system (210, 410, 710), characterized by:

a programmable load (M1..M8) connected to the antenna system for transmission modulation.

2.   An RF transponder, according to claim 1, characterized in that the programmable load comprises:

a plurality of first output stage transistors (M1..M4) connected to a first terminal (VA) of the antenna system;

a corresponding plurality of second output stage transistors (M5..M8) connected to a second terminal (VB) of the antenna system; and

control logic (747) for determining which ones of the first output stage transistors and which ones of the second output stage transistors are used to modulate the antenna system.

3.   An RF transponder, according to claim 2, characterized by:

an EEPROM (436, 436b) storing programmed settings for driving the control logic.

4.   An RF transponder, according to claim 1, characterized by:

a power supply (Vxx) and level shifters (LS1..LS4) connected to the programmable load, wherein voltage changes in the power supply dynamically vary a magnitude of the programmable load according to power available in the transponder.

5.   An RF transponder, according to claim 1, characterized by:

a gate (796) for disconnecting modulation of the antenna system in response to a reset signal.

6.   An RF transponder (102, 200, 400), comprising:

an antenna system (210, 410, 710), characterized by:

a dynamically variable load (700), comprising:

a load (M1..M8) connected to the antenna system for transmission modulation; and

a power supply (Vxx) and level shifters (LS1..LS4) connected to the load, wherein voltage changes of the power supply dynamically vary the magnitude of the load according to power available in the transponder.

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7.   An RF transponder, according to claim 6, characterized in that:

the dynamically variable load further comprises elements for programmable variation of the magnitude of the load on the antenna system, the elements comprising:

a plurality of first output stage transistors (M1..M4) connected to a first terminal (VA) of the antenna system;

a corresponding plurality of second output stage transistors (M5..M8) connected to a second terminal (VB) of the antenna system; and

control logic (747) for determining which ones of the first output stage transistors and which ones of the second output stage transistors are used to modulate the antenna system.

8.   An RF transponder, according to claim 7, characterized by:

an EEPROM (436, 436b) storing programmed settings for driving the control logic.

9.   An RF transponder, according to claim 6, characterized by:

control logic (747) connected for modulating the dynamically variable load, wherein the control logic has a control signal input (PSK_MOD, $\overline{PSK\_MOD}$) formed in a gate (794) by logically combining a system clock signal (SYS_CLK/2) and a data stream (DATA STREAM).

10.   An RF transponder, according to claim 9, characterized by:

a sync delay circuit (792) for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

11.   An RF transponder, according to claim 6, characterized by:

a gate (796) for interrupting modulation of the antenna system in response to a reset signal.

12.   An RF transponder (102, 200, 400), comprising:

an antenna system (210, 410, 710); and

circuitry (246, 446, 700) for applying modulation to an RF signal received by the antenna system, characterized by:

a modulation load (M1..M8) connected to the antenna system;

control logic (747) for controlling the modulation load;

a first gate (794) providing a control signal (PSK_MOD, $\overline{PSK\_MOD}$) to the control logic, wherein the first gate logically combines a system clock signal— .

AMENDED SHEET

(SYS_CLK/2) and a data stream (DATA STREAM); and

     a sync delay circuit (792) for delaying the system clock signal in order to synchronize the system clock signal with the data stream.

13.   An RF transponder, according to claim 12, characterized by:

     a second gate (796) interposed between the first gate and the control logic for disconnecting modulation of the antenna system in response to a reset signal.

14.   Method for controlling RF signal modulation in a passive transponder which comprises an antenna system (210, 410, 710), circuitry (246, 446, 700) for applying modulation to an RF signal received by the antenna system, and circuitry (222, 422) for deriving transponder power from the received RF signal, characterized by:

     providing a modulation load (M1..M8) connected to the antenna system and modulated under the control (747) of a control signal (PSK_MOD, $\overline{PSK\_MOD}$) formed by logically combining (794) a.system clock signal (SYS_CLK/2) and a data stream (DATA STREAM); and

     delaying (792) the system clock signal in order to synchronize the system clock signal with the data stream.

15.   Method, according to claim 14, characterized by:

     forming a phase-shift keyed type of control signal, for producing phase-shift keyed modulation of the RF signal received by the antenna system.

16.   Method, according to claim 15, characterized in that:

     the phase-shift keyed control signal uses a system clock signal having half the frequency of the RF signal received by the antenna system; and

     the data stream is a signal clocked at a fraction of the frequency of the RF signal received by the antenna system.

17.   Method, according to claim 16, characterized in that:

     the fraction is one-thirty-second (1/32)

18.   Method, according to claim 14, characterized by:

     optimizing RF signal modulation performance by utilizing a modulation index having a magnitude which is adjusted according to programmed trim settings stored (436b) in the transponder.

19.   Method, according to claim 18, characterized by:

   binary adjustment of the modulation index as determined by bits of the

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programmed trim settings.

20.   Method, according to claim 14, characterized by:

a modulation index having a magnitude which is adjusted dynamically in proportion to a power of the RF signal received by the antenna system.

5   21.   Method, according to claim 14, characterized by:

preventing RF signal modulation if the power derived from the RF signal received by the antenna system is too low to provide transponder power adequate for stable transponder operation including RF signal modulation.

1/8

Figure 1
Prior Art

Figure 2

3/8

Figure 3

Figure 3A

254

Fosc'

360 Capture Temp

362 Capture Press

321
(253)

255

257

to 246

240

12-TO-1 MUX

232 TEMPERATURE REGISTER

234 PRESSURE REGISTER

Figure 3B

370

Vcc

Vbg +

− 372

Vdd

P

N
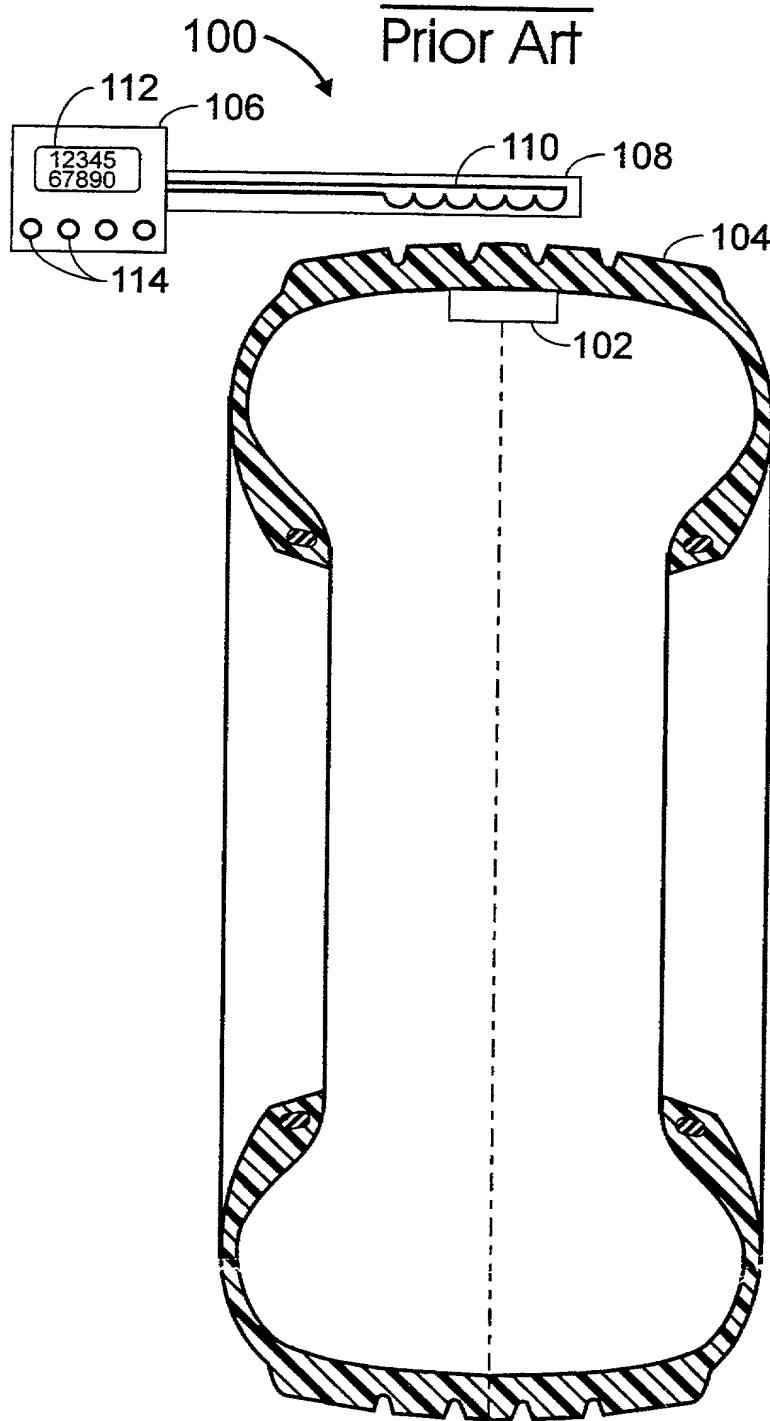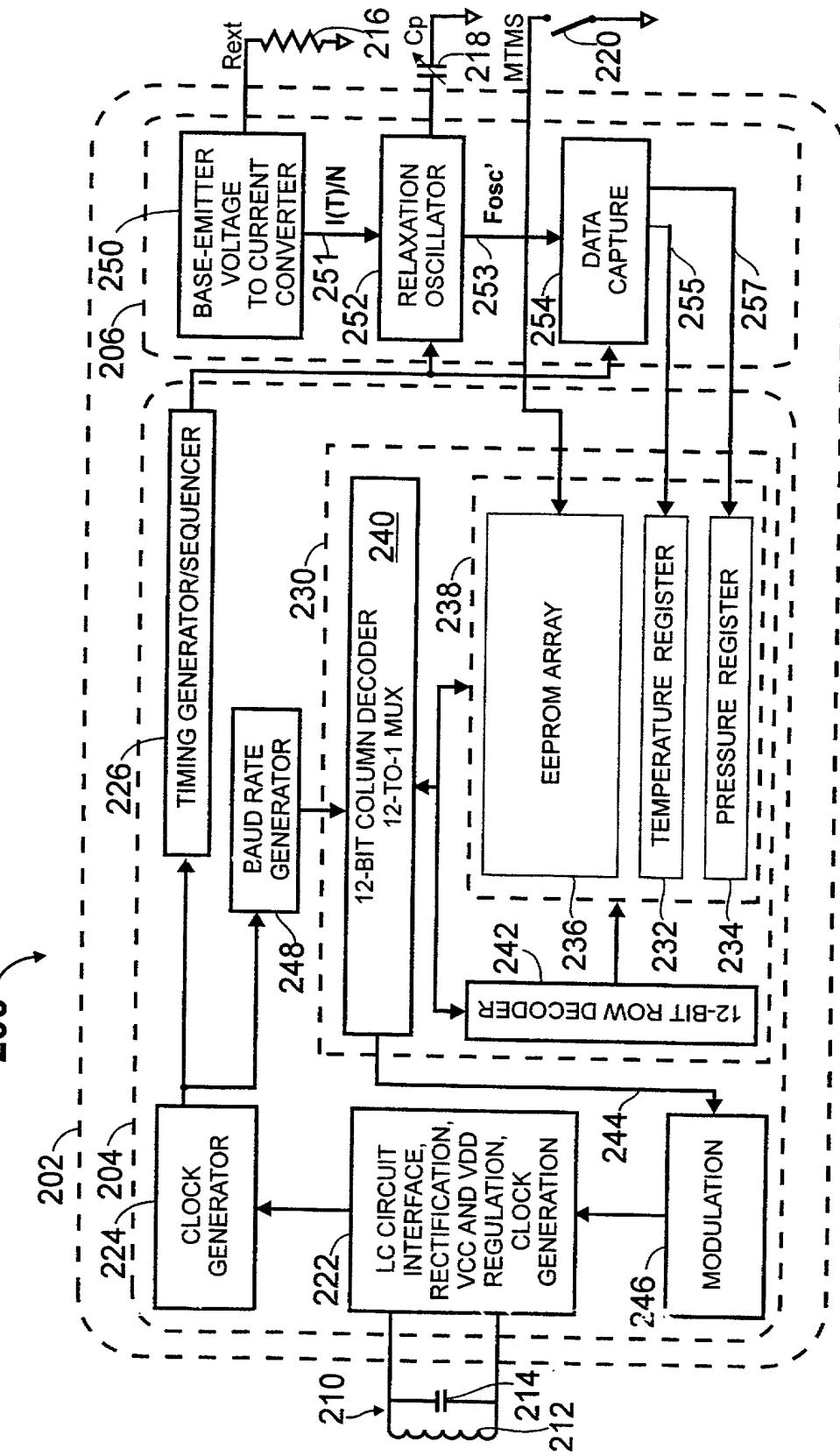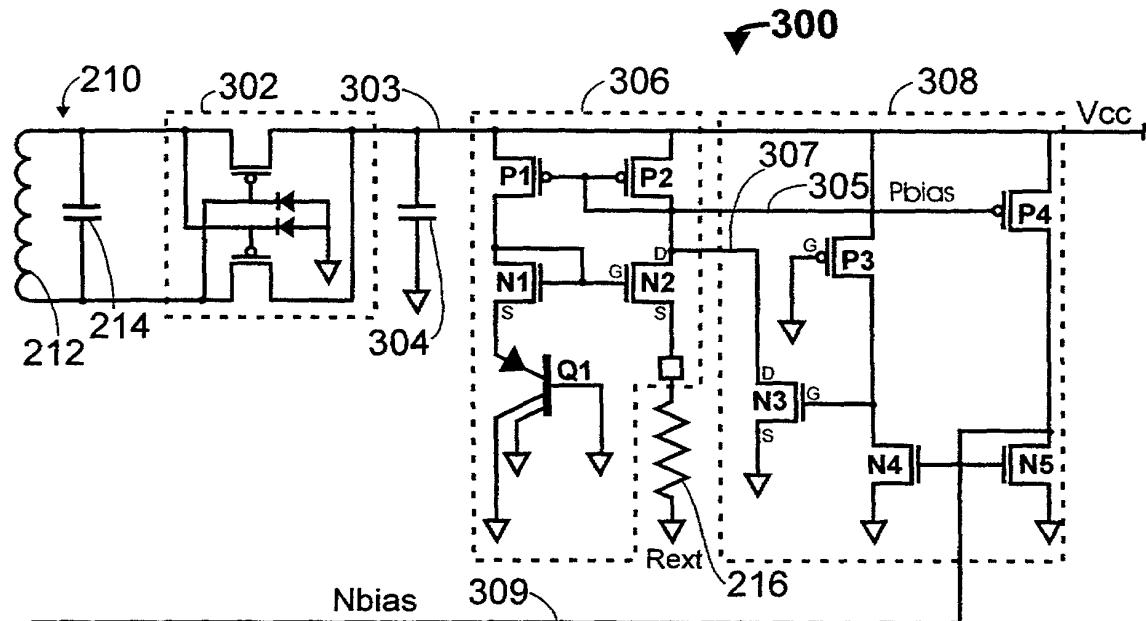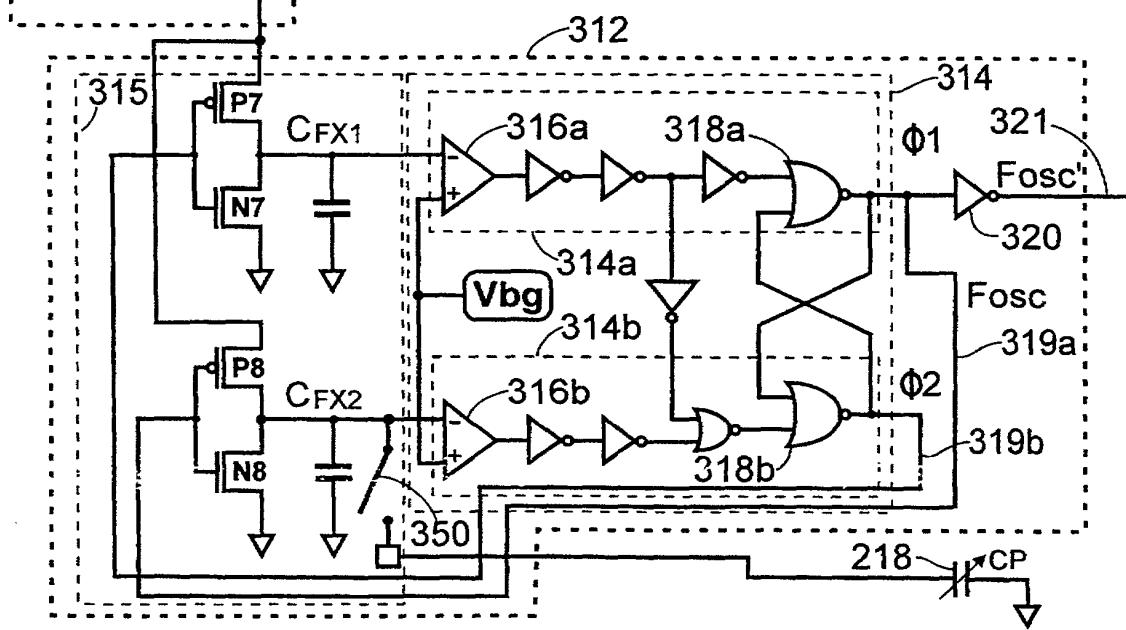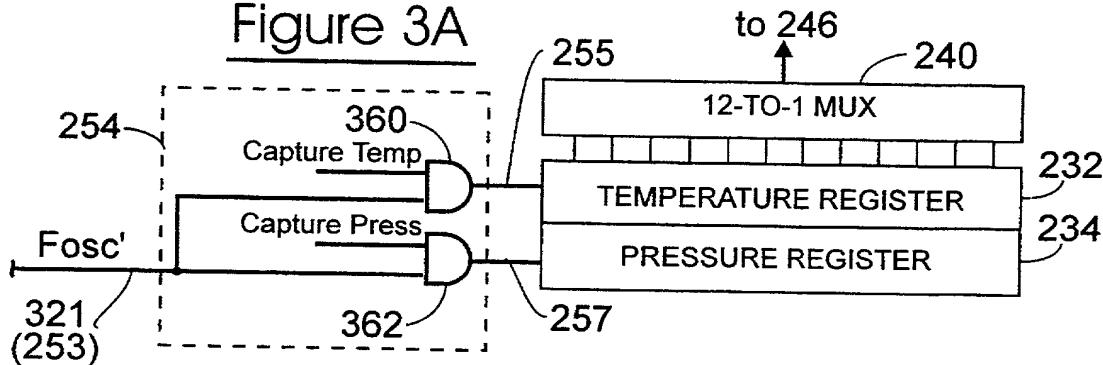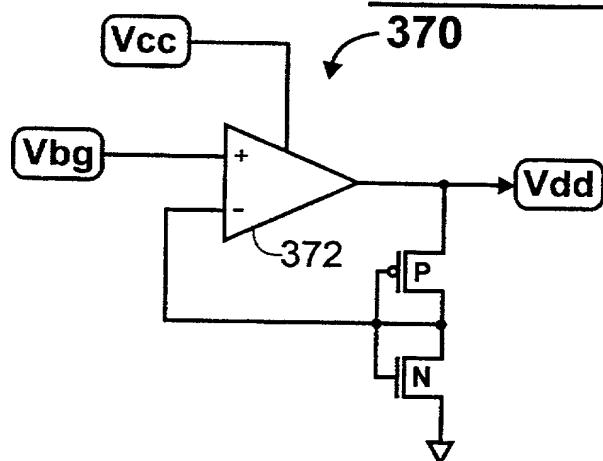
Figure 3C

◄—— 12 COLUMNS ——►

ROW 1	SYNC 000..011
ROW 2	DATA 012..023
ROW 3	DATA 024..035
ROW 4	DATA 036..047
ROW 5	DATA 048..059
ROW 6	DATA 060..071
ROW 7	DATA 072..082, MTMS 083
ROW 8	TEMP COMP 084..095
ROW 9	PRESS COMP 096..107
ROW 10	TEMP/PRESS SLOPES 108..113, 114..119
ROW 11	TEMP COUNT (NT) 120..131
ROW 12	PRESS COUNT (NP) 132..143
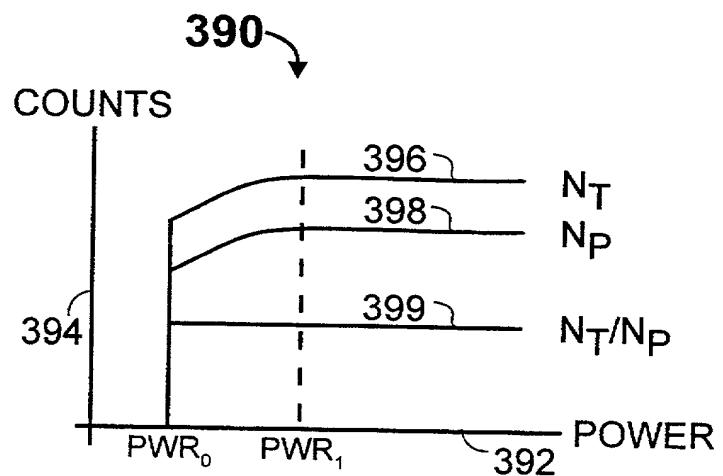
Figure 3D

Figure 4A
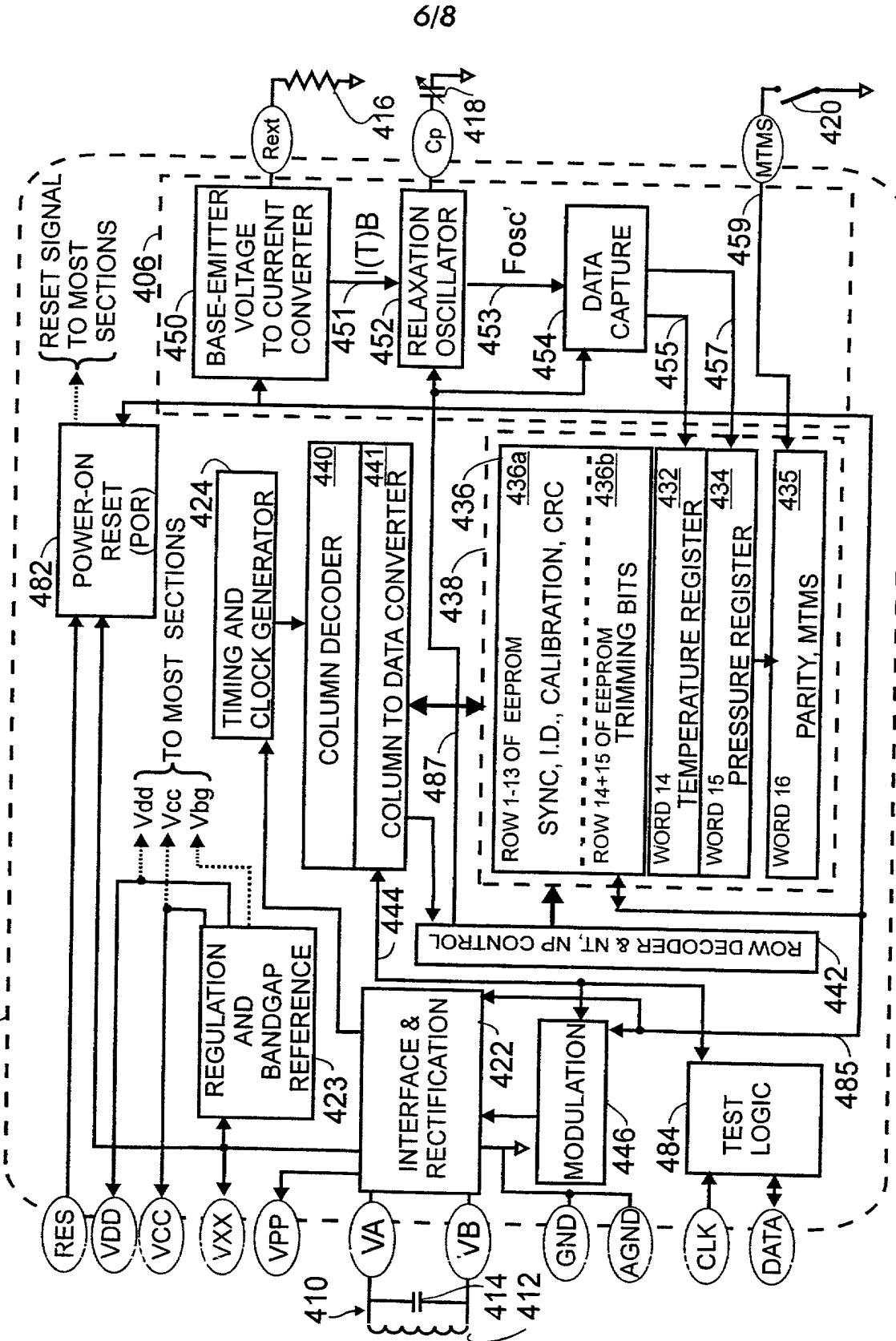
Figure 4B

EEPROM LOCATION	DATA STREAM	← 12-BIT WORDS →	
ROW 1	WORD 1	SYNC WORD (12)	12-BIT SYNC WORD
ROW 2	WORD 2	ID (12)	
ROW 3	WORD 3	ID (12)	48 BITS OF USER ID
ROW 4	WORD 4	ID (12)	
ROW 5	WORD 5	ID (12)	
ROW 6	WORD 6	TEMPERATURE CALIBRATION (12)	
ROW 7	WORD 7	TEMPERATURE CALIBRATION (12)	48 BITS OF TEMPERATURE & PRESSURE CALIBRATION DATA
ROW 8	WORD 8	PRESSURE CALIBRATION (12)	
ROW 9	WORD 9	PRESSURE CALIBRATION (12)	
ROW 10	WORD 10	CHIP ID (12)	
ROW 11	WORD 11	CHIP ID (12)	36 BITS OF TRANSPONDER CHIP ID
ROW 12	WORD 12	CHIP ID (12)	
ROW 13	WORD 13	CAL ID (4) · CRC (8)	4-BIT CALIBRATION ID AND 8-BIT CRC
	WORD 14	TEMPERATURE NT (12)	TEMPERATURE (NT) AND PRESSURE (NP) DATA REGISTERS
	WORD 15	PRESSURE NP (12)	
	WORD 16	OPEN (5),MTMS(1) NP, NT PARITY(6)	11111, MTMS STATUS, AND PARITY OF NP, NT DATA

|			
ROW 14		TRIMMING BITS (12)	12-BIT TRIMMING REGISTER
ROW 15		TRIMMING INVERSE BITS (12)	

Figure 5

700
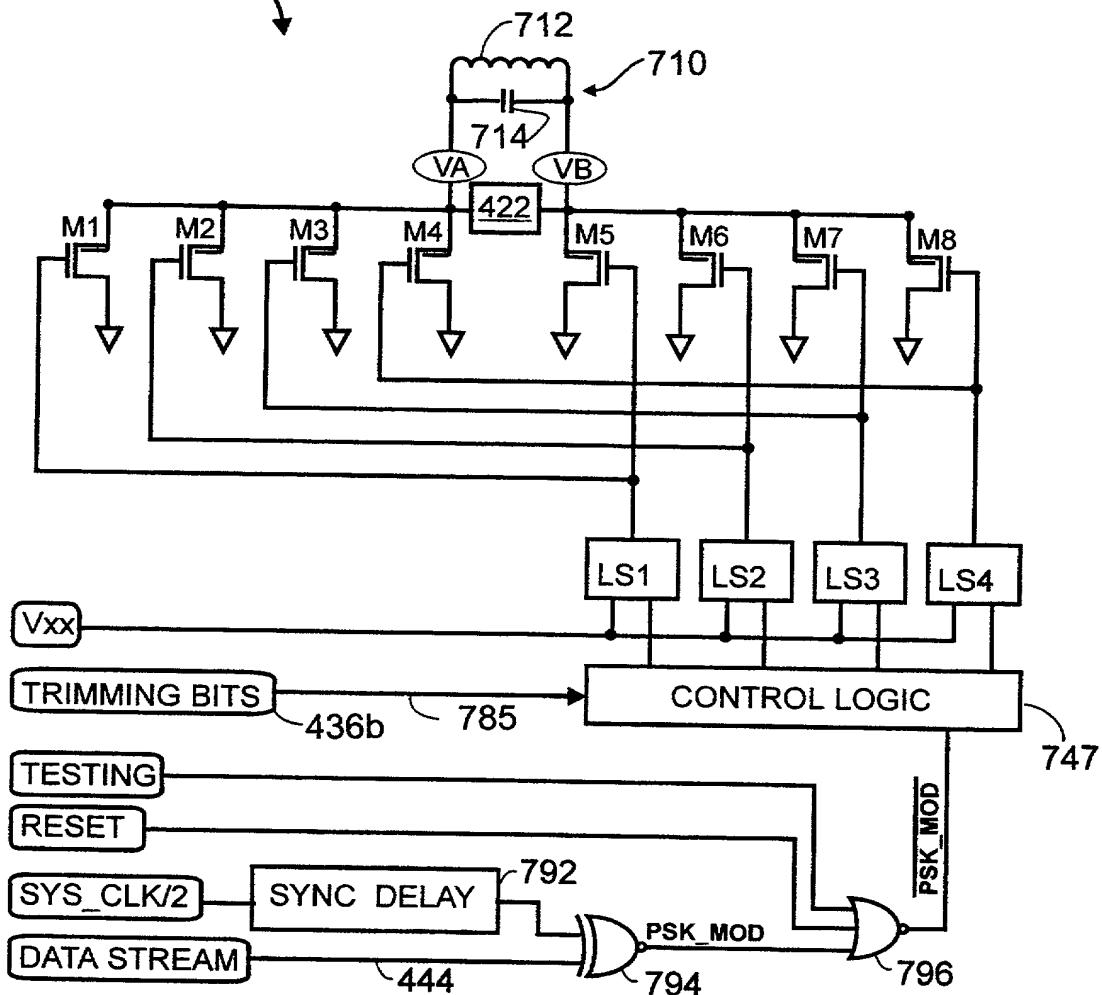
Figure 5A

747a

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled PROGRAMMABLE MODULATION INDEX FOR TRANSPONDER the specification of which (check one)

_____ is attached hereto.

__X__ was filed on __December 15, 1999__ as Application Serial No. __PCT/US99/29827__ and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 C.F.R. § 1.56.

I hereby claim the benefit under 35 U.S.C. § 119(c) of any United States provisional application(s) listed below:

60/134,460	May 17, 1999
(Application Serial No.)	(Filing Date)

I hereby claim the benefit under 35 U.S.C. § 120 of any United States application(s) or § 365 of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. § 112, I acknowledge the duty to disclose material information as defined in 37 C.F.R. § 1.56 which become between the filing date of the prior application and the national or PCT international filing date of this application:

(Application Serial No.)	(Filing Date)	(Status)(patented, pending, abandoned)

POWER OF ATTORNEY

As named inventor(s), I or we hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

David L. King	Registration No.	33,925
David E. Wheeler	Registration No.	29,726
Howard M. Cohn	Registration No.	25,808
Nancy T. Krawczyk	Registration No.	38,744

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statement may jeopardize the validity of the application or any patent issuing thereon.

Full name of sole or first inventor (given name, family name) __Dale Lee Yones__

Inventor's signature _____ Date _____

Residence __Boulder, Colorado U.S.A.__ Citizenship __U.S.A.__

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☐ Additional inventors are being named on separately numbered sheets attached hereto.

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